Demonstration of Nitrate-Enhanced In Situ Bioremediation at a Petroleum Hydrocarbon Contaminated Site

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Alternative strategies involving in situ remediation technologies have been developed to assist with property clean up, however, cost-effectiveness and discrepancies in success rates and timeliness continue. The objective of my research was to critically demonstrate the application and usefulness of an in situ remediation technology at a petroleum hydrocarbon impacted site. This project was proposed as part of the research programs: Groundwater Plume Formation and Remediation of Modern Gasoline Fuels in the Subsurface and Enhancing In Situ Bioremediation at Brownfield Sites funded by the Ontario Centres of Excellence for Earth and Environmental Technologies as part of the multiphase project entitled "Enhancing in situ Bioremediation at Brownfield Sites".

This research focused on the demonstration of nitrate-enhanced in situ bioremediation at a decommissioned service station. Petroleum hydrocarbon impacted soil and groundwater is a common occurrence at gasoline distribution facilities, where toxicological effects are known for gasoline constituents of interest such as benzene, toluene, ethylbenzene and total xylenes (BTEX). These chemicals are volatile, readily soluble, and persistent in groundwater. In particular, residual contaminants present in the saturated zone were targeted for remediation as they serve as a long term source of contamination and contribute to mobile vapour phase and dissolved phase plumes. Site investigations characterized the complex hydrogeological conditions and contaminant distribution present in order to effectively design an in situ bioremediation treatment system.

The addition of nitrate as a terminal electron acceptor (TEA) to an aquifer enhances in situ biodegradation of petroleum hydrocarbons, by providing the microbes with a sustainable energy source to promote cell maintenance and growth of the microbial population. The remediation strategy involved pulsed injections of remedial solution amended with a conservative bromide (200 mg/L Br^-) and reactive nitrate (90 to 265 mg/L NO_3^-) tracers with the purpose of providing a continuous supply of TEA available to the indigenous microbial populations. Nitrate was selected as an alternative electron acceptor over the thermodynamically favoured O_2 because of typical challenges encountered using O_2 in bioremediation applications in addition to the existing anaerobic environment. In situ anaerobic degradation of BTEX compound using TEA amendments has been well documented; however benzene is often recalcitrant under denitrification conditions.

The results of the Br^- tracer breakthrough curves indicate that different preferential flow pathways were established under the transient saturated conditions present at the Site, although the behaviour of the injected remedial slug was generally consistent between the different units and the test solution was ultimately delivered to the target zone. The delivery of the remedial test solution was greatly influenced by the hydrogeological conditions present at the time of injection. The injectate was preferentially transported in the high permeability zone of sandy gravel aquifer Unit 3 under high saturated condition and background hydraulic gradients. However the seasonal decline in groundwater levels and hydraulic gradients resulted in the lower portion of Unit 4 comprised of higher permeable materials being able to transmit the test solution more effectively.

Given the variable hydrogeological conditions present at the Site influenced by seasonal effects, the delivery of the remedial solution to target zones containing petroleum hydrocarbons at residual saturation is more effective under reduced saturated conditions. The delivery of TEA amended water to enhance the in situ biodegradation of petroleum contaminants is more effective when the treatment water has an increased residence time in the target remedial zone, attributed to low gradients and groundwater transport velocities at the Site. Longer residence periods enable the indigenous microbes to have increased contact time with the TEA which will be preferentially utilized to degrade the contaminants.

A reducing zone enriched with TEA in the anaerobic aquifer was established following consecutive injections of remedial test solution. A cumulative mass of 4 kg of NO_3^- was added to the target aquifer during the course of the remedial injections. Evidence demonstrating NO_3^- utilized as a terminal electron acceptor in the bioremediation of the petroleum-contaminated aquifer include: laboratory microcosm study confirming local indigenous microbial population's ability to degrade hydrocarbons using NO_3^- as the TEA in addition to observed decrease in NO_3^- relative to a conservative Br^- tracer and generation of nitrite, an intermediate product in denitrification in the pilot-scale operation.

Contaminant mass removal likely occurred as Br^- tracer evidence indicates that NO_3^- was utilized in the study area based on the inference of denitrification rates. Post-injection groundwater sampling indicate declining concentrations of toluene, however long term monitoring is recommended in order to evaluate the success of the remediation activity and assess the potential for rebound. Post-injection soil core results are unable to demonstrate the reduction in individual toluene, let alone BTEXTMB hydrocarbon levels, as a result of insufficient quantities of nitrate delivered to the target zone relative to the significant but heterogeneously distributed residual mass in the subsurface.

Acknowledgements

I am grateful for the wonderful opportunity my supervisor Dr. Jim Barker provided me for my thesis. His guidance, expertise and mentoring helped me to address the many challenges encountered with both the research and my own demons. Jim patiently supported me throughout the various trials, tribulations and chapter edits. Jim was always readily available, be it in person or via email, which became particularly necessary when I moved to Ottawa in my final year to pursue a career in hydrogeology. I would also like to thank the following members of my committee; Dr. Barb Butler for introduced me to the wonders of microbiology and Dr. Will Robertson for provided expertise and insight on the unique hydrogeological characteristics of the research site. Thank you both for reviewing and providing feedback on this work.

Special thanks to the SNC Lavalin Inc. team I worked with including Susan Froud, Allison Reid MacFadden, Jacqueline Kreller and Lane Cavalier and providing me access to the study site. I was given a unique opportunity of working in collaboration with and learning from skilled contaminated groundwater management professionals. I am truly fortunate to have had the pleasure of working with Allison throughout various stages of my research. Her support, commitment and enthusiasm towards the project from beginning to end is very much appreciated. We managed to do a fine job entertaining ourselves and shared some pretty good times while overcoming challenges and mysteries encountered in the field.

A significant amount of field information was gathered throughout the various stages of the project. My research was made possible by an incredible task force of researchers and fellow students. Marianne VanderGrient proved an invaluable resource for my analytical chemistry, soil extraction and microcosm needs. Thank you for analyzing countless groundwater and soil cores that often required several dilutions. I would also like to thank Shirley Chatten, Justin Harbin, Wayne Noble, Ralph Dickout, Cynthia Nixon, Leah Siczkar, Xuu Zhang and Dave Dilworth for laboratory support. Field investigations could not have been possible without the help of Bob Ingleton who provided excellent technical guidance and support from the preliminary stages to the design and implementation of the in situ remediation system. I would also like to thank Paul Johnson, Bobbie Adams, Jenny Lambert, Trevor Tompkins, Lily Whitehead, Marcelo Sousa, Dr. Juliana Freitas, Kate Critchley, Adam Fuller, Bobby Katanchi, Neelmoy Biswas and Matt Schumacher who also assisted me along the way, whether it be in the field, lab or during countless discussions trying to figure out what may actually be occurring at the site, within the realms of hydrogeology.

I am thankful to Shell Canada Products, the Ontario Centres of Excellence, Petro Canada, Solinst, SNC Lavalin Inc, the American Petroleum Institute and the National Sciences and Engineering Council of Canada for providing generous financial support.

Finally, thank you to my family and friends who continued to support me throughout this lengthy journey. One advantage of taking a little extra time completing my Masters was having the opportunity to befriend a new batch of eager graduate students every fall. Thank you all for the memorable University of Waterloo experience.

Dedication

I would like to dedicate this thesis to my parents who have provided me with everlasting love and support while following my dreams and passions.

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Chapter 1: Introduction

1.1 Overview

Research was conducted as part of a multiphase project entitled ‘Enhancing in situ Bioremediation at Brownfield Sites’, funded by the Ontario Centres of Excellence for Earth and Environmental Technologies. This project was proposed as part of the research programs: Groundwater Plume Formation and Remediation of Modern Gasoline Fuels in the Subsurface and Enhancing In Situ Bioremediation at Brownfield Sites.

A brownfield site consists of an idle or abandoned industrialized property that has often been subject to soil and/or groundwater contamination as a result of historic land use practices. An estimated 30,000 brownfield sites are present in Canada to which many consist of water fronts, former refineries, railway yards, service stations and commercial properties that utilized hazardous chemicals (NRTEE, 2003).

Brownfield properties tend to be situated in prime locations and in close proximity to existing infrastructure. Their clean up and potential for redevelopment has the ability to provide economical, social and environmental benefits to the local community. These properties typically have a high land reuse value, where reclamation of former industrial sites for affordable housing and infrastructure can be a lucrative activity depending on site remediation costs and market prices. Remediation strategies involve the mitigation and/or removal of contaminants that have the potential to cause a risk to health thereby improving the overall social and environmental well being of the community.

To encourage redevelopment, existing brownfield legislation provides property owners with general protection from environmental cleanup orders for historic contamination once they have appropriately remediated a site to meet specific standards. Brownfield reclamation in Ontario is subject to the Record of Site Condition Regulation (O. Reg. 153/04) which contains specifications related to site assessment and remediation targets according to its classified land use. A Record of Site Condition (RSC) is a statement filed by a qualified person that is issued after completing a Phase II Environmental Site Assessment. A RSC is required whenever a property undergoes changes in ownership or is utilized for more sensitive land applications.

The revitalization of former industrial sites is an environmentally sound and sustainable approach to meeting the demands of economic and population growth while reducing urban sprawl, preserving green spaces and agricultural lands (NRTEE, 2003). Redevelopment of these contaminated properties is often problematic due to the nature and extent of the contamination present, however land use restrictions and engineering controls may be applied to reduce the risk. Popular practices for mitigating soil and groundwater compliance issues involves off-site remedies or removal of contaminated materials, referred to as ex situ treatment that may involve excavation of impacted soil that exceeds generic criteria through dig and dump techniques and groundwater pump and treat systems. Ex-situ treatment can be beneficial as the process can be completed within an intermediate time-frame and is advantageous in land acquisition scenarios. However, ex situ treatment and/or disposal of soil and contaminated groundwater to hazardous waste facilities can be costly or non-practical given the amount of contamination present.

Alternative strategies involving in situ remediation technologies have been developed to assist with property clean up, however, cost-effectiveness and discrepancies in success rates and timeliness continue. The objective of my research is to critically demonstrate the application and usefulness of an in situ remediation technology at a decommissioned gasoline service station. Petroleum hydrocarbon impacted soil and groundwater contamination is a common occurrence in brownfield sites relating to fuel storage and distribution facilities. In particular, residual contaminants present in the saturated zone will be targeted for remediation. The mitigation of the migration and occurrence of contaminants in the subsurface requires that the site specific mechanisms driving groundwater solute transport be well understood and addressed in the design and implementation of an in situ groundwater remediation system. The research project involved site investigations to characterize the hydrogeological conditions and contaminant distribution present in order to effectively design an in situ bioremediation treatment system.

1.2 Site Description

The site consists of a former gasoline service station with petroleum hydrocarbon impacted soil and groundwater in a rural setting. Former underground storage tanks and fuel lines were excavated and removed as part of the service station decommissioning in 1999. Site characterization and management have been conducted by SNC Lavalin (formerly Aqua Terre Solutions Inc) since 1999 and monitoring continues to the present day. The main components of concern of the petroleum hydrocarbon impacted aquifer include water soluble gasoline constituents benzene, toluene, ethylbenzene, xylenes (BTEX), in which soil and groundwater criteria have been consistently exceeded at the Site designated as a potable groundwater source for industrial/commercial/community property use for coarse textured soils, Table 2 (MOE, 2004).

The nature of the petroleum hydrocarbon contamination present consists of free phase NAPL, dissolved phase plume emanating from the source zone, residual and soil gas impacts. Remedial efforts implemented thus far by SNC Lavalin include on a few occasions removal of NAPL by vacuum truck and the installation of two passive skimmers for retrieval of NAPL in the source zone. Geochemical analyses conducted during groundwater sampling programs have been used to assess the property for possible remediation through natural attenuation, and this is discussed in further detail in Chapter 2.

1.3 Subsurface Contamination

Historical Site investigation carried out by SNC-Lavalin included borehole drilling, installation of monitoring wells, collection of soil and groundwater samples for analysis of petrochemicals in order to identify and manage the migration of contaminants in the subsurface.

BTEX compounds exceed the soil and drinking water quality standards for the Site, which is subject to Table 2 standards (MOE, 2004). The environmental management program implemented at the Site involves bi-annual groundwater quality monitoring at select impacted and non-impacted wells both on and formerly off-site (adjacent land acquired in 2010) to delineate and monitor the attenuation of the dissolved contaminant plume. Soil and groundwater samples collected during SNC-Lavalin Inc. sampling events are submitted to and analyzed by the accredited Maxxam Analytics laboratory. A map of the location of select monitoring wells is presented in Figure 1.1, with monitoring wells containing BTEX concentrations above MOE Table 2 standards for contaminated sites highlighted, as determined from the groundwater sampling program conducted on April 27, 2010.

The nature of the petroleum hydrocarbon contamination present consists of a vapour phase, free phase NAPL and a dissolved phase plume emanating from the source zone. The 2010 dissolved phase BTEX plume exceeding MOEE standards currently measures 22 m long with a maximum width of 18 m, which is a decrease from previous groundwater quality results where the plume had a maximum width of 24 m in 2001. The distribution of the contaminant plume is controlled by longitudinal elongation and location of former USTs. A summary of the historical groundwater quality results collected by ATSI –SNC Lavalin Inc. is presented in Appendix A.

Remedial efforts that have been implemented thus far include the installation of two passive skimmers for retrieval of NAPL in monitoring wells MW-1 and MW-102 and on a few occasions in 2007 removal of NAPL by vacuum truck. The release of petroleum hydrocarbons to the groundwater resulted in the development of a reducing contaminant plume present at the Site.

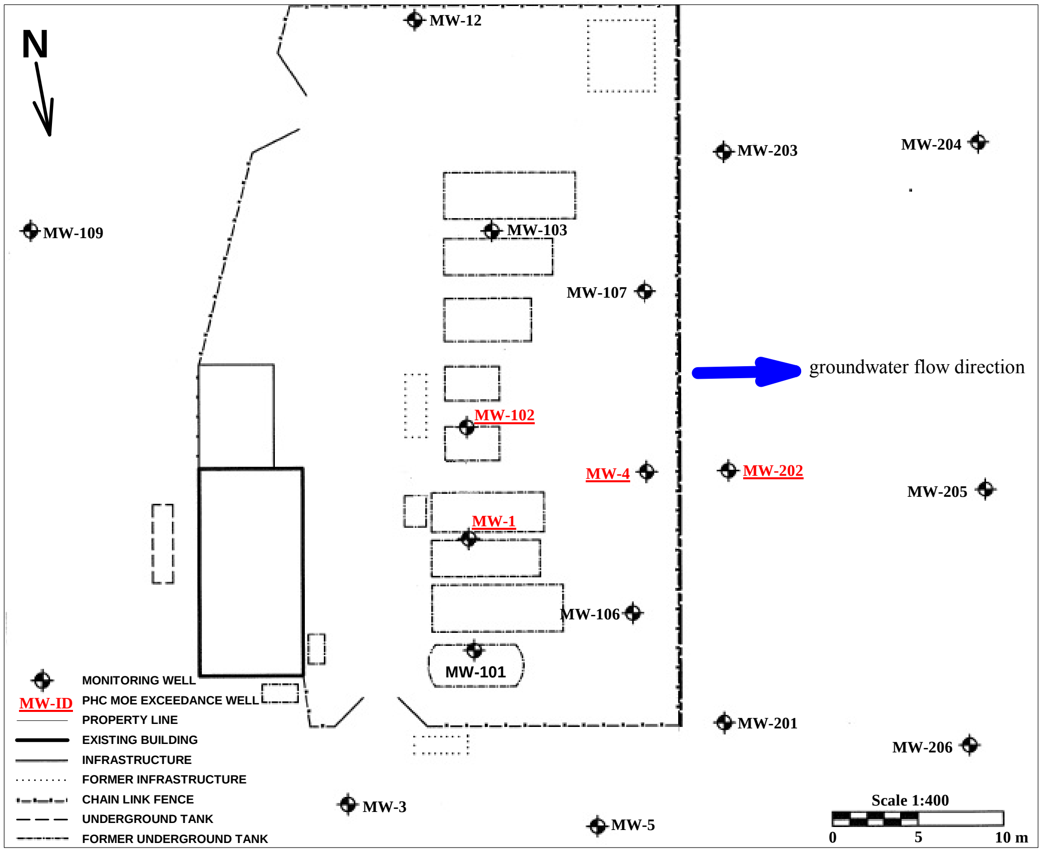

Figure 1.1: Location of existing SNC-Lavalin monitoring wells. Well IDs that appear in red contain aromatic hydrocarbons in exceedence of Table 2 MOE (2004) standards.

1.4 Enhanced In Situ Bioremediation

Natural attenuation involves the natural environment's (subsurface) ability to recover from damage sustained from the release of contaminants via natural processes such as biodegradation, dilution, dispersion and sorption, which limits the transport of contaminants in groundwater and thus reduces impacts to sensitive receptors. Natural attenuation is influenced by geochemical (oxidation-reduction processes, presence of electron acceptors), biological (indigenous microbial populations) and physical characteristics (hydraulic gradients, porosity, heterogeneity) of the aquifer. Indigenous microbes present in the subsurface are capable of utilizing select organic pollutants as a carbon and energy source in the metabolism and synthesis of cells and as a result, contaminants are degraded.

Hydrogeological conditions are variable from site to site and the behaviour of the pollutant(s) is subject to the subsurface conditions in addition to physical (sorption and adsorption), chemical (oxidation and reduction) and biological processes (aerobic or anaerobic biodegradation). The implementation of a suitable remediation system at a contaminated site requires an understanding of the hydrogeological conditions present and expertise on the selected remediation technology(ies) (Sims et al., 1992). The feasibility of in situ bioremediation application(s) is also influenced by the location of the contaminant source, whether it be above or below the water table.

In situ bioremediation utilizes the same processes of natural attenuation; however the strategy involves the addition of terminal electron acceptors (TEA) (oxygen, nitrate, sulphate or iron III) to the aquifer to enhance natural degradation processes. The addition of O_2 (air sparging, hydrogen peroxide) to promote aerobic respiration is the most thermodynamically favourable TEA for microbes in the oxidation of hydrocarbon compounds. However, challenges associated with the use of O_2 additions include rapid utilization, low solubility in water and possible reduced hydraulic conductivity as a result of excessive microbial growth and iron precipitates clogging the porous media. An alternative approach involves the anaerobic treatment using nitrate as a TEA. Advantages of nitrate include higher solubility, more cost-effective than O_2, while minimizing unwanted reactions with non-target dissolved metals such as Fe(II). Nitrate addition has the ability to enhance bioremediation of the target aromatic compounds, however it has not been demonstrated to stimulate the biodegradation of the saturated hydrocarbon fraction of gasoline.

1.5 Nitrate as a Terminal Electron Acceptor

The objective of this thesis is to evaluate the potential for injecting nitrate (NO_3^-) as a terminal electron acceptor to enhance the bioremediation of residual hydrocarbons in a complex sand/gravel unconfined aquifer. In order to mitigate the migration and occurrence of contaminants in the subsurface, the site specific mechanisms driving groundwater solute transport must be well understood and addressed in the design and implementation of an in situ groundwater remediation system. Nitrate was selected as an alternative electron acceptor over the thermodynamically favoured O_2 because of typical challenges encountered using O_2 in bioremediation applications.

Nitrate in groundwater systems may originate from decaying plant material or anthropogenic processes associated with agricultural practices such as the excessive application of fertilizers that leach into the groundwater supply and pose a potential health risk. NO_3^- removal from the subsurface system is mediated by abiotic chemical transformations and biotically by indigenous microbes that utilize the electron acceptor as an energy supply to promote further growth and development.
The nitrogen (N) cycle is comprised of a number of redox reaction pathways as described in Figure 1.2, where N is either assimilated into organic compounds or dissimilated from organic matter.

Denitrification involves the microbial reduction of NO_3^- to intermediate products nitrite (NO_2^-), nitric oxide (NO^-), nitrogen oxide (N_2O) and the final product elemental nitrogen (N_2) with the use of an electron donor such as organic carbon, equation (1.1) (e.g. Stumm & Morgan, 1981):

$$NO_{3\,(aq)}^{-} \rightarrow NO_{2\,(aq)}^{-} \rightarrow NO_{\text{(enzyme complex)}} \rightarrow N_2O_{(g)} \rightarrow N_{2(g)} \qquad (1.1)$$

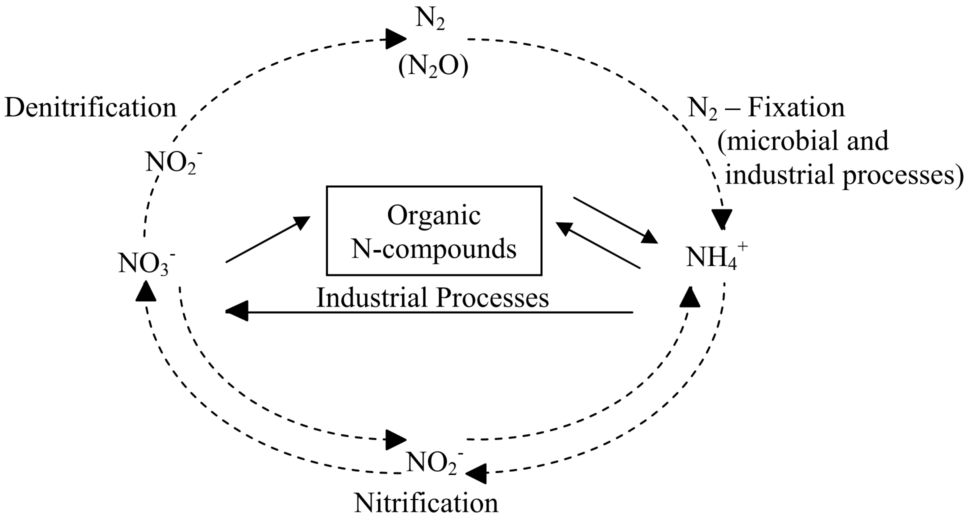

Figure 1.2: Nitrogen cycling during redox reactions (from Appelo & Postma, 2005).

Denitrification results in the production of intermediary products NO_2^- and NO^-; both pose a potential health threat to the groundwater supply and are regulated by Ontario Drinking Water Quality Standards (ODWQS). The maximum acceptable concentration of NO_2^- in drinking water is 1 mg NO_2^-N mg/L, where in the event NO_3^- and NO_2^- are both present, their combined concentration must not exceed 10 mg/L as N (e.g. MOE, 2003).

Nitrate reduction in groundwater systems by organic matter has been well documented by Korom (1992) and Starr & Gillham (1993), to name a few. Denitrification can be carried out by facultative heterotrophic bacteria, utilizing organic constituents (Kaplan et al., 1984). The most common genera of denitrifiers are *Pseudomonas*, followed by *Alcaligenes* (Zehnder, 1988). *Pseudomonas* and *Alcaligenes* are capable of synthesizing nitrate reductase (NAR) and growing in the presence of O_2 and NO_3^- (Krul, 1976; Krul & Veeningen, 1977).

The microorganisms present at the Site have been exposed to the petrochemicals for years to decades, where evolution and adaptations have taken place in order for the organisms to succeed in the petroleum hydrocarbon contaminated environment (Riser-Roberts, 1998). The pre-existing anoxic aquifer conditions may serve as an indicator that microbes are established and actively biodegrading petroleum hydrocarbons. However, the indigenous microbes have not historically been exposed to an abundant supply of NO_3^- and their ability to degrade organic contaminants via denitrification is being evaluated. The stoichiometry of the overall reaction of denitrification using organic matter is shown in equation (1.2) (e.g. Pederson et al, 1991; Korom, 1991):

$$5CH_2O + 4NO_3^-{}_{(aq)} + 4H^+ \rightarrow 5CO_{2(g)} + 2N_2 + 7H_2O_{(l)} \tag{1.2}$$

Geochemical species present in the reduced groundwater environments, where denitrification is actively occurring may also serve as electron donors including Fe^{2+}, H_2S and CH_4. However, these compounds are not as thermodynamically favourable and are limiting compared to the organic contaminants present, therefore they likely only play a limited role as electron donors. For example, the oxidation of iron sulphide is presented in equations (1.3) and (1.4) (e.g. Kolle et al, 1983; Postma et al., 1991; Robertson et al., 1996):

$$5FeS_2 + 14NO_3^-{}_{(aq)} + 4H^+ \rightarrow 7N_2 + 10SO_4^{2-}{}_{(aq)} + 5Fe^{2+}{}_{(aq)} + 2H_2O_{(l)} \tag{1.3}$$

$$5Fe^{2+}{}_{(aq)} + NO_3^-{}_{(aq)} + 12H_2O_{(l)} \rightarrow 5Fe(OH)_3 + \tfrac{1}{2}N_2 + 9H^+ \tag{1.4}$$

Nitrate can also be transformed assimilatory into ammonia (NH_3) where N is taken up and incorporated into biomass or dissimilated into ammonium (NH_4^+) during nitrate reduction in groundwater systems (Smith et al, 1991). However, the latter does not represent a dominant process. Dissimilatory nitrate reduction to ammonium (DNRA) is presented in equation (1.5) from Tiedje et al. (1982):

$$2H^+{}_{(aq)} + NO_3^-{}_{(aq)} + 2CH_2O \rightarrow NH_4^+ + 2CO_2 + 2H_2O \tag{1.5}$$

Denitrification is predominantly favoured in the reducing environments because it yields more metabolic energy compared to DNRA (e.g. Korom, 1992), which tends to be limited by electron acceptor availability (Tiedje, 1988). DNRA is regulated by O_2 that leads to N_2 as previously demonstrated in equation (1.1) or reduction to NH_4^+ equation (1.6).

$$NO_3^- \rightarrow NO_2^- \rightarrow NH_4^+ \tag{1.6}$$

Facultative bacteria are capable of growth under anaerobic conditions utilizing NO_3^-or NO_2^-, however anaerobic and facultative anaerobic bacteria are capable of dissimilatory nitrate reduction to NH_4^+ (e.g. Zehnder, 1988). Ammonium production during the denitrification process involving the consumption of organic compounds may occur in groundwater systems, however not in great amounts (e.g. Smith et al, 1991; Appelo & Postma, 2005).

In situ anaerobic degradation of BTEX compound using TEA amendments has been well documented (e.g. Acton & Barker, 1992; Barbaro et al., 1992; Barker et al., 1987; Hutchins et al., 1991a). NO_3^- has been successfully used to accelerate the bioremediation of monoaromatic hydrocarbons, gasoline constituents toluene, ethylbenzene and xylenes, however benzene was recalcitrant (e.g. Barbaro et al., 1992, Reinhard, 1994). NO_3^- has also demonstrated to be used in the biodegradation of polyaromatic hydrocarbons (PAHs), however, it has not been shown to degrade aliphatic compounds (Brown, Mahaffey, & Norris, 1993). Biodegradation of higher molecular weight hydrocarbons by denitrification may result in an increased number of intermediate oxidation products, which may accumulate to inhibitory level, where the alcohols of C5 to C9 alkanes were inhibitory (Bartha & Atlas, 1977).

Chapter 2: Site Characterization

2.1 Geographic Setting

The Site consists of a former gasoline service station decommissioned in 1999 situated in a small rural community in southwestern Ontario. Petroleum hydrocarbon impacted soil and groundwater are present at the Site related to historic operational activities. Details pertaining to the specific location of the research Site are not disclosed; however a map describing the proximity to housing, agricultural operations and the local waterway are presented in Figure 2.1. The Site is situated 311 m above mean sea level (m AMSL) for the given area (Google Earth, 2010), where groundwater elevations were approximated in relation to an arbitrary benchmark used during monitoring well surveying.

Figure 2.1: Aerial view of the research Site situated in southwestern Ontario, 1995 (MTO, 1995).

2.2 Site Geology

The geology at the Site is highly heterogeneous unconsolidated sediments consisting of various fine to medium grain sand, silty sand and gravelly sands identified through coring investigations. Geological mapping of the area indicates that surficial deposits in the area consist of a glaciofluvial outwash sand lobe with minor gravel deposits located within the Elma till that originated during the Pleistocene Late Wisconsinian period (Cowan et al., 1986). Stratigraphic mapping of the surficial materials indicate that outwash materials were deposited as stratified drift consisting of sand and gravel materials laid down in smooth and gently sloping plains (Hoffman & Richards, 1954). Coring investigations are consistent with this. Sand and gravel units interlaid with till and lacustrine silty sand layers have been observed during Site characterization, whereby these deposits likely developed during periods of glacial surging. Grain-size analyses on sediments cored demonstrate poor to moderate sorting of unsaturated zone and aquifer materials.

Drilling at the Site has been to an assumed elevation of 298 m AMSL, within unconsolidated material, where drift thickness maps and nearby borehole records estimate 15-20 m (296-291 m AMSL) of overburden material in the area (Kelly & Carter, 1993; MOE, 2011). The underlying bedrock is comprised of grey-brown limestone and dolostone of Middle-Devonian Detroit River Group (Freeman, 1978) and at one time had been mined for aggregate at a former nearby quarry.

2.3 Site Instrumentation

The Site is well characterized with a monitoring network comprised of 32 wells. The monitoring network is equipped with wells installed by SNC-Lavalin and University of Waterloo monitoring wells installed as part of the research project in a specified study area. The distribution of wells in the monitoring network and the location of the area where research was focused on are presented in Figure 2.2. A summary of the well details is presented in Appendix A (Table A.1 and A.2), with accompanying borehole logs.

The property was initially instrumented with 17 monitoring wells installed by SNC-Lavalin Inc. for aquifer monitoring and characterization located upgradient, downgradient and beyond the zone of influence of former petroleum service station operations. SNC-Lavalin monitoring wells are screened between 311.47 and 300.95 m AMSL and are comprised of 0.051 m or 0.102 m inner diameter PVC well materials containing a 3.05-7.62 m 0.00254 m slotted screen.

Additional monitoring wells were installed in a selected study area on three separate occasions by licensed well drillers (Geo Environmental Drilling Inc.) as part of the research project. Four multilevel wells were installed as part of the research project in November 2007 to determine the vertical distribution of the contaminants in the groundwater. The multilevel wells identified as MW-301, MW-302, MW-303 and MW-304 consist of a 0.0127 m inner diameter (ID) PVC centre stock pipe surrounded by several 0.00635 m ID low-density polyethylene tubing pieces screened at various depths below the ground surface at 1 m intervals from 308.81 to 298.13 m ASML. All wells contained a 0.20 m slotted interval wrapped with 200 µm Nytex ® mesh screen.

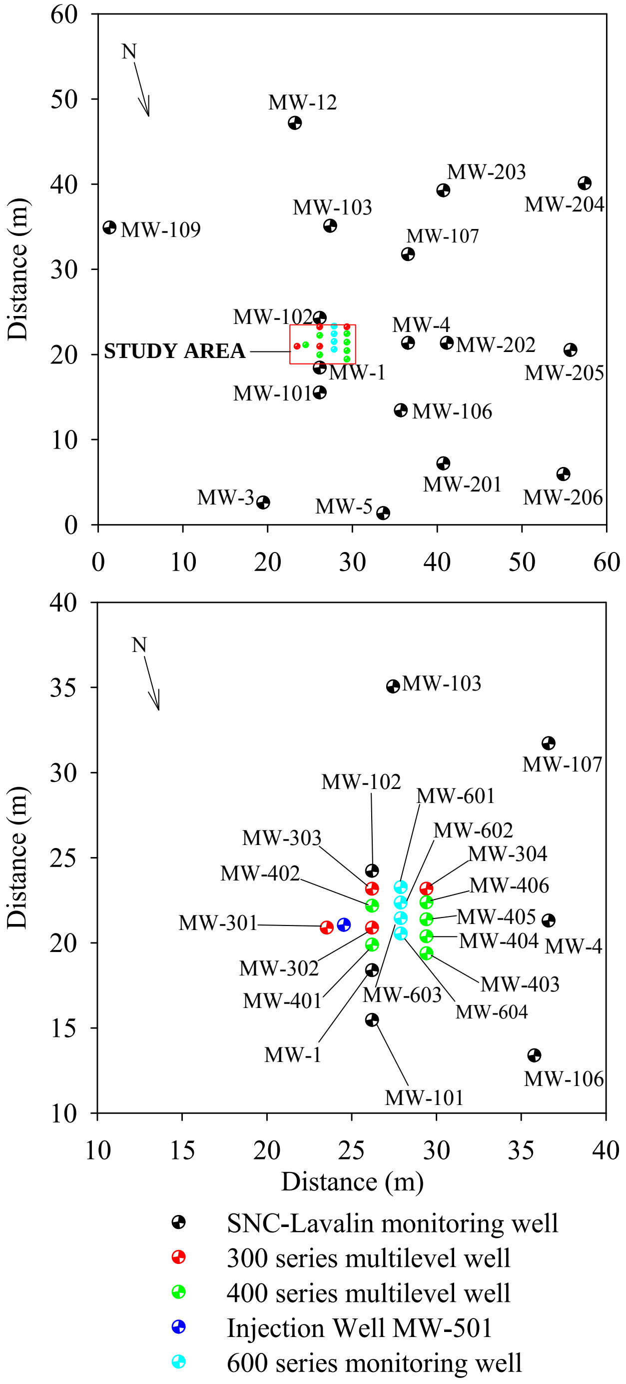

Figure 2.2: Plan view map identifying groundwater monitors present at the site.

Another set of multilevel wells were installed in July 2009 to serve as part of a remediation system monitoring network. The multilevel wells MW-401, MW-402, MW-403, MW-404, MW-405 and MW-406 are constructed of 0.019 m ID PVC centre stock surrounded by 8 0.0127 m ID low-density polyethylene tubing pieces screened at 0.5 m intervals between 5 and 9.5 m below ground surface (310.40 to 315.09 m AMSL). All wells contained a 0.5 m slotted interval wrapped with 200 µm Nytex ® mesh screen. Injection well MW-501 comprised of 0.051 m ID PVC well material equipped with a 2 m 0.00254 m slotted screen interval, 306.09 to 301.40 m AMSL was also installed at this time to deliver the remedial solution.

The study area was equipped with 4 additional wells (600 series) as part of a separate research project conducted by another University of Waterloo M Sc. Bobby Katanchi in October 2009. The wells were used in conjunction with the 300 and 400 series multilevel wells used as part of evaluation of the remediation system. Wells MW-601, MW-602, MW-603 and MW-604 were constructed of 0.0254 m ID dense PVC tubing containing a 0.50 m well screen and wrapped with 200 µm Nytex ® mesh screen. The 600 series wells are screened between 304.11 and 302.40 m AMSL.

2.4 Site Hydrogeology

The Site hydrogeology consists of a shallow unconfined aquifer in heterogeneous unconsolidated materials. The water table undergoes seasonal variability, ranging on average from 309.5 to 304.5 m AMSL (1.5 m to 6.5 m bgs). The sediments are comprised of 5 distinct geological units from the surface: (1) 4-5 m sand and gravel fill, (2) 1 m sand (3) 2-2.5 m sand and gravel, (4) 1-4 m sand, (5) sand and gravel to the extent of the drilling investigation, 298 m AMSL (13 m bgs). See cross-section depicted in Figure 2.3.

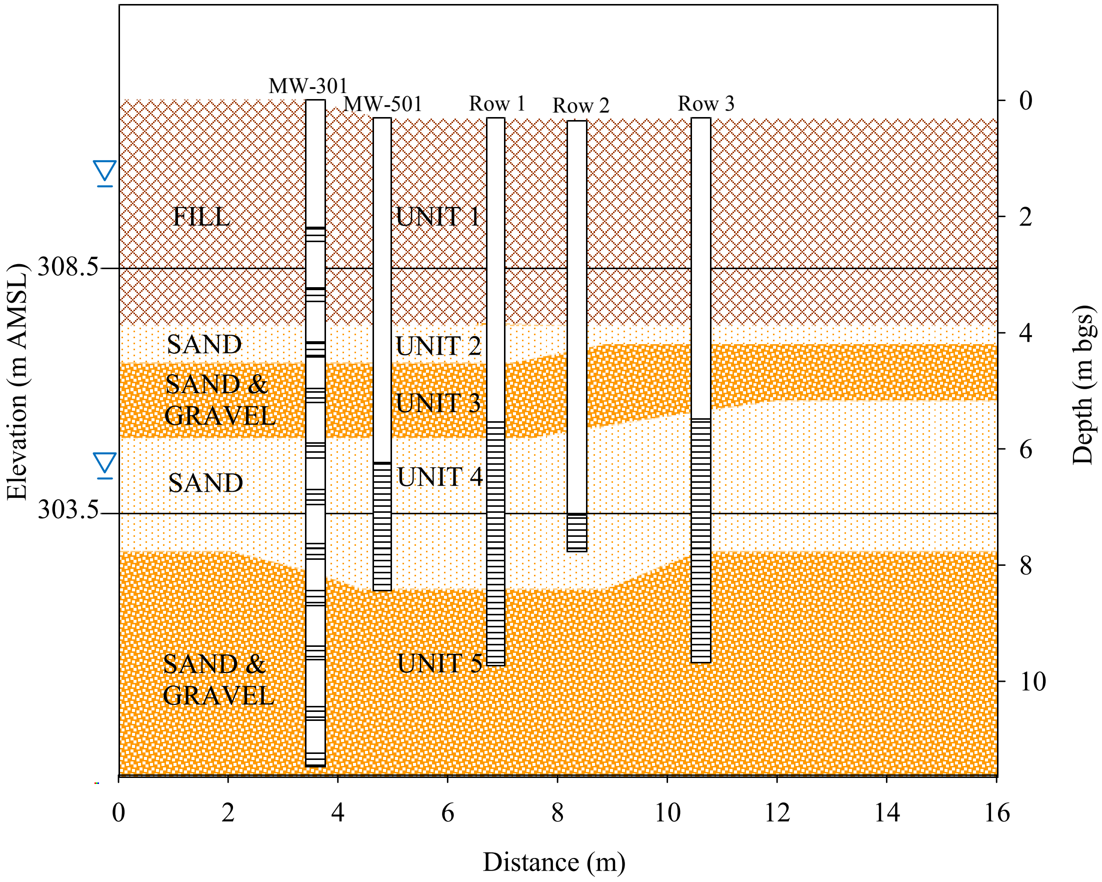

Figure 2.3: Conceptual geologic cross-section of the research Site within the selected study area. Historical water table range (309.5 – 304.5 m AMSL), spatial distribution and screened intervals of monitoring and multilevel wells also shown.

2.4.1 Seasonal Water Table Fluctuations

Groundwater elevations in shallow unconfined aquifers are susceptible to seasonal changes. The groundwater elevation fluctuates an average of 4 m annually based on historic monthly monitoring data spanning from 2004-2010, presented in Figure 2.4. The largest recorded seasonal water level rise occurred between December 2007 and April 2008, where the water table level increased by 5.9 m. Water table levels have declined as much as 4.6 m within a year during March and October 2006. Maximum water table elevations historically occur after spring recharge while low levels are present in the fall.

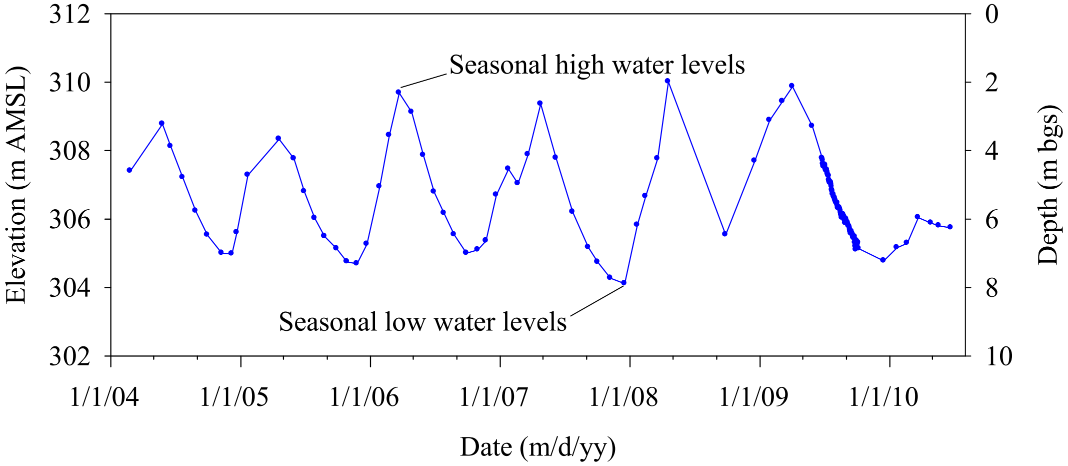

Figure 2.4: Seasonal groundwater elevation fluctuations in MW-101. Note: 2009-2010 recharge period is distinguished from the previous seasonal changes. (SNC-Lavalin, 2004-2010)

Variability in water table elevation is influenced by a number of factors that include the hydraulic and geometric parameters of the aquifer, areal extent of the recharge area, boundary conditions, rate and duration of recharge and discharge events whether they are natural or anthropogenic in origin (Rai & Singh, 1995). The decline in water table elevation during the summer months corresponds to increases in evapotranspiration, temperature increases and the growing season (e.g. Lyford, 1964) which could be contributing to water levels losses at the Site related to agriculture practices occurring in close proximity (less than 100 m to the west and downgradient from the Site).

The large level fluctuations may also indicate loss of groundwater as subsurface outflow (Neupane & Shrestha, 2009), however field data suggest negligible downward gradients are present based on the select portion of the aquifer under investigation. Small head differences are difficult to detect relying solely on water level data, as a result or possibly related to measurement error and local variability in vertical gradients induced by aquifer heterogeneities (Silliman & Mantz, 2000; Elçi et al., 2003). Vertical drawdown gradients exist for the general area (Waterloo Hydrogeologic Inc., 2003), however given the maximum extent of aquifer characterization is to 298 m AMSL, vertical gradients may be more pronounced in a deeper zone of the aquifer.

Interactions between the local surficial and bedrock geology with agricultural land use practices may be responsible for the transient hydrogeological conditions observed. River depth information collected from a river located approximately 800 m north of the Site indicate evidence of a hydrogeological connection between the local groundwater system and surface water body based on similar observed behaviour of fluctuating river depth (Saugeen Valley Conservation Authority, 2005-2010), and groundwater elevations (Figure 2.5).

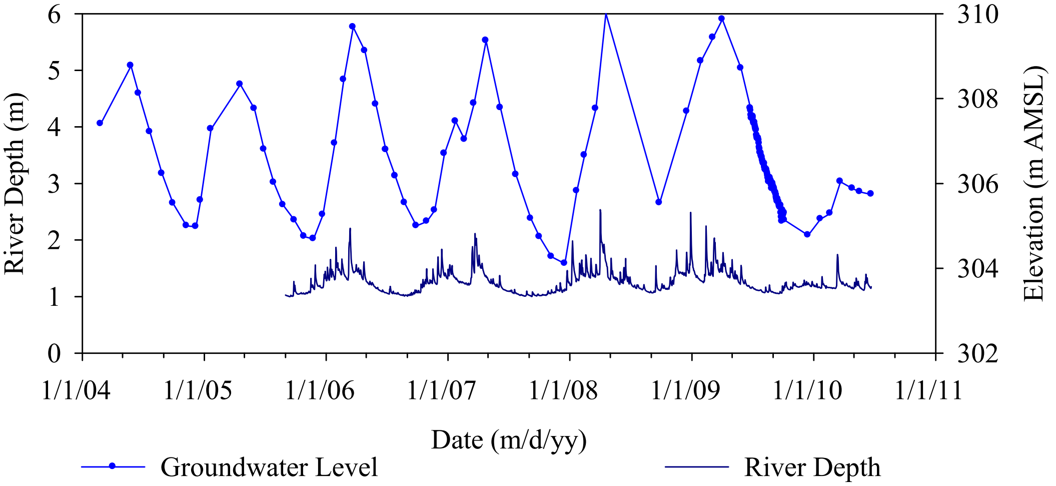

Figure 2.5: Seasonal groundwater fluctuations at the Site and corresponding to daily river depths. (SNC-Lavalin, 2004-2010; SVCA, 2005-2010)

Seasonal groundwater fluctuations are also influenced by the amount of precipitation that contributes to diffuse aquifer recharge as shown in Figure 2.6, where water level rise is proportionate to the amount of recharge that occurs and can be highly variable, influenced by topography and depth to water table (Alley et al., 2002). The topography of the Site is relatively flat, where similar oscillating water levels have been measured at various monitoring wells located within the study area. Delin et al. (2007) developed a method to illustrate precipitation can contribute at least 21% to aquifer recharge. By applying the Delin et al. (2007) method, a maximum 26% water table rise would be attributed to precipitation at the Site assuming 100% contributes to aquifer recharge, which is not highly realistic. Therefore, additional hydraulic and geometric parameters of the aquifer, boundary conditions and areal extent of the recharge area must also be influencing seasonal fluctuations of the water table.

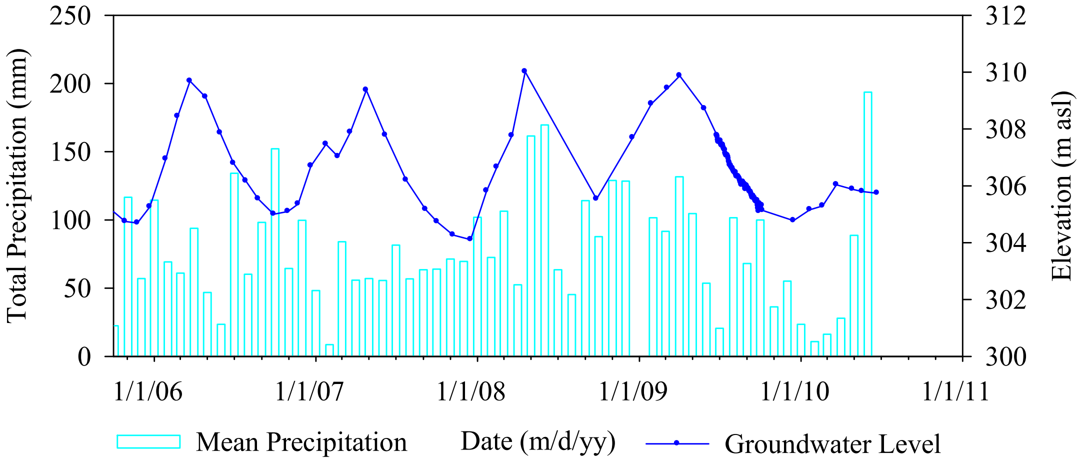

Figure 2.6: Seasonal groundwater fluctuations at the Site and corresponding to mean monthly precipitation (SNC-Lavalin, 2006-2010; SVCA, 2005-2010)

Aquifer recharge between December 2009 and March 2010 was limited to 1.27 m, which is significantly less than characteristic recorded events onwards of 4 m. Only 20% of the typical amount of cumulative precipitation fell during that time span (0.07 m compared to an average of 0.34 m for similar seasonal recharge periods from 2005-June 2010). A summary of the approximate aquifer recharge periods, water table recharge heights and rates corresponding to local precipitation data is presented in Table 2.1.

Table 2.1: Summary of seasonal and average aquifer recharge, recharge rates and recharge periods corresponding to local seasonal precipitation data.

Start Period Date	End Period Date	Precipitation (m)	Seasonal Recharge (m)	WTR (% of Precipitation)	Rate of Recharge (m/day)	Recharge Rate R^2
07-Dec-04	19-Apr-05	na	3.25	-	0.024 ± 0.006	0.87
11-Nov-05	23-Mar-06	0.38	4.99	25	0.044 ± 0.003	0.98
30-Oct-06	27-Apr-07	0.36	4.26	28	0.022 ± 0.003	0.92
17-Dec-07	18-Apr-08	0.38	5.90	21	0.045 ± 0.004	0.98
26-Sep-08	02-Apr-09	0.51	4.33	40	0.023 ± 0.002	0.99
12-Dec-09	22-Mar-10	0.07	1.27	18	0.012 ± 0.003	0.91
Average (s.d)		**0.339 (0.164)**	**4.02 (1.59)**	**26 (9)**	**0.028 (0.013)**	**0.94 (0.05)**

Note: % of precipitation = Recharge (from precipitation) = Δ water level * specific yield, assumed to equal porosity (0.32) in unconfined aquifer; na – data not available, s.d – standard deviation, WTR – water table recharge

The rate of aquifer recharge occurring at the Site remains fairly constant throughout the recharge period, where an average recharge rate of 0.028 m/day, $R^2 = 0.94$) was determined from single monthly water level measurements. Recharge rates vary between seasons; however they are not readily influenced by short term precipitation events based on daily precipitation data and continuous water level data collected from MW-101 equipped with a datalogger.

Declining water levels typically occur from March to late fall (October-November), where water levels decrease an average of 4 m. A comparison between the seasonal declining water table periods, degree and rate of the lowering water table is presented in Table 2.2. Linear regression analysis indicates that a good correlation exists for the discharge rates within one season, where an average discharge rate of 0.02 m/day, $R^2 = 0.95$ was obtained between 2006 and 2009. It must be noted that recharge and discharge rates determined from monthly frequencies often results in an underestimate of rates Delin et al. (2007) and actual rates could be higher than presented in Table 2.2.

Table 2.2: Summary of seasonal and average aquifer discharge, discharge rates and discharge periods.

Start Period Date	End Period Date	Seasonal Discharge (m)	Rate of Discharge (m/day)	Discharge Rate R^2
26-May-06	07-Dec-04	3.79	0.020 ± 0.002	0.96
19-Apr-05	24-Nov-05	3.64	0.018 ± 0.002	0.95
23-Mar-06	30-Oct-06	4.58	0.023 ± 0.002	0.94
20-Mar-07	17-Dec-07	3.77	0.019 ± 0.003	0.88
2-Apr-09	06-Oct-09	4.53	0.012 ± 0.001	0.99
Average (s.d)		**4.06 (0.45)**	**0.018 (0.004)**	**0.95 (0.04)**

s.d – standard deviation

Earlier discussion on the geology of the Site in Section 2.2 characterized the general area as glacial outwash units interlaid with till deposits. Bradley (1954) states that water table fluctuations in glacial till can measure 1.5-4.6 m whereas stratified sand and gravel typically undergo fluctuations < 1 m seasonally, related to capillary effects of the porous media.

2.4.2 Transient Groundwater Flow Conditions

Groundwater flow is horizontal with an estimated velocity of less than 1 cm/day to 43 cm/day based on single-well point dilution tests described in further detail in Section 2.6.2. The minimum average linear groundwater velocity typically coincides with low seasonal groundwater levels and is at a maximum during peak water table levels as presented in Figure 2.7. The horizontal gradient at the Site is primarily to the west ranging between 0.003 and 0.02 seasonally determined from monthly water level measurements obtained from wells consistently screened across the water table interface, typically MW-103, MW-101 and MW-107 or MW-4 (Appendix A, Table A.3). The wells are located approximately 14-23 m apart from one another. During seasonal low water table, differences between the hydraulic heads can be minimal (<0.05m) which increases the uncertainty associated with specific horizontal hydraulic gradient measurements.

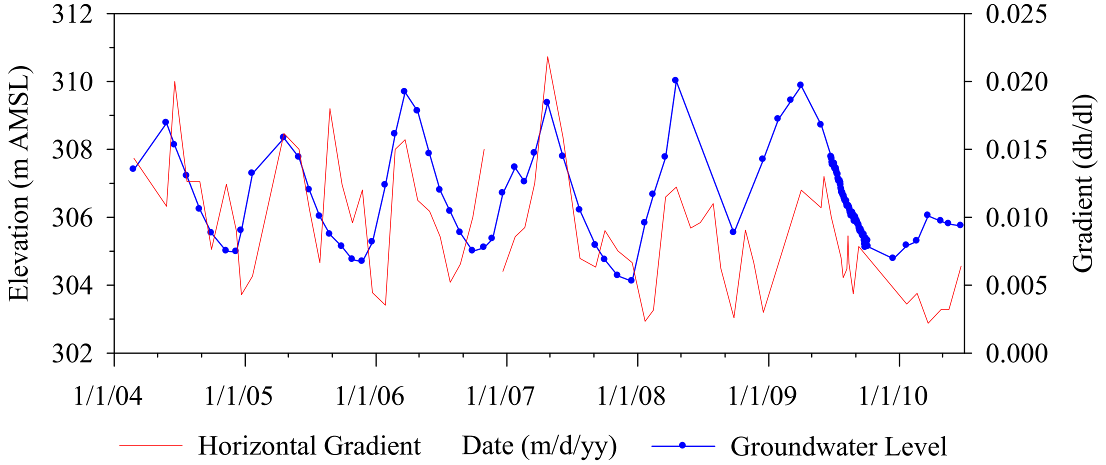

Figure 2.7: Seasonal gradient and groundwater elevations (MW-101) at the Site inferred from water table elevations of MW-101, MW-103 and MW-107 or MW-4.

The mean and standard deviation of the seasonally variable groundwater flow direction is S83°W, and 17°, respectively as determined from historical water table data collected during monthly monitoring events between 2004- June 2010. The interpreted direction of groundwater flow is in the west-southwest direction in the late winter – early spring during periods of recharge and maximum water table elevations, then drifting towards the west throughout the summer as the water table declines. Groundwater flow is towards the north-northwest in the fall-winter during periods of minimum water table elevations, as demonstrated in Figure 2.8 and Table A.3.

The transient nature of the hydrogeological conditions present at the Site may also be in accordance with the behaviour of aquifers located in close proximity to a groundwater divide (Doss, 1993). Physical hydrogeological characteristics near a groundwater divide include large seasonal water table fluctuations, variable groundwater flow directions and low hydraulic gradients (Toth, 1963). In order to better understand the driving force behind the transient groundwater flow conditions, a large-scale water balance budget is required for the local watershed that is beyond the scope of this research. The large magnitude in water table variability is of particular interest at the Site due to the redistribution and re-mobilization of petroleum hydrocarbons which will be discussed in further detail in Chapter 3.

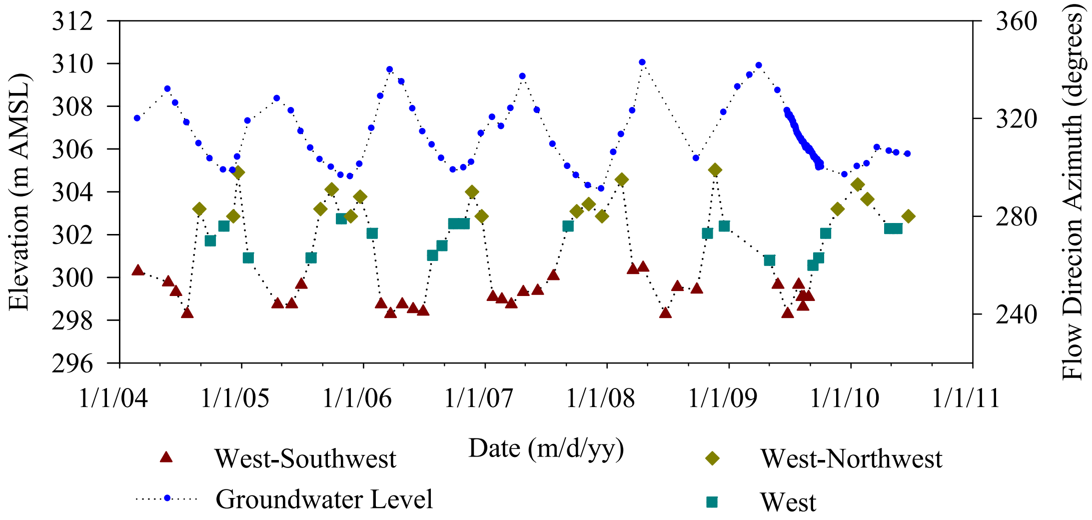

Figure 2.8: Variability in seasonal groundwater flow direction. Southwest – winter to summer, West – mid-late summer and Northwest – fall to early winter.

2.5 Aquifer Geochemistry

Groundwater monitoring and sampling for petroleum hydrocarbons and select inorganic species has been conducted by SNC Lavalin to evaluate the extent of the contaminant plume since 1999 and assess the potential for monitored natural attenuation by measuring the utilization of electron acceptors and accumulation of biodegradation by-products. Wells were monitored for field parameters, geochemical indicators of biodegradation, BTEX and F1-F4 petroleum hydrocarbons. Field parameters were collected simultaneously with dissolved oxygen (DO) measurements using a YSI 556 Multi-parameter meter (temperature, pH, oxidation reduction potential (ORP), conductivity), with results presented in Appendix A, Table A.4.

2.5.1 Dissolved Oxygen

Field DO readings were collected by direct down-well measurements on a monthly basis from April 2007 to December 2009, where measurements were taken approximately 0.3 m below the water table interface. Aerobic and anaerobic zones of the aquifer were delineated using the observed DO concentrations.

Background DO levels within the aerobic portion of the aquifer range between 4-8 mg/L, where impacted wells located on the fringe of the contaminant plume have DO levels up to 4 mg/L. Anaerobic conditions exist strictly in the source zone and petroleum-impacted areas exceeding groundwater quality standards specified for Table A industrial/commercial criteria for fine/medium textured soils in a potable groundwater condition (MOE, 1997). The anaerobic zone of the aquifer is defined as groundwater containing DO levels < 2 mg/L. Anoxic aquifer conditions may be an indicator that hydrocarbon degrading microbial populations are established and actively biodegrading contaminants of interest.

Dissolved oxygen measurements fluctuate seasonally in both the aerobic and anaerobic zones of the aquifer, identified by monitoring wells MW-12 and MW-103, respectively (Figure 2.9). The dissolved oxygen levels measured in the non-petroleum hydrocarbon (PHC) impacted (MW-12) and PHC impacted aquifer (MW-103) oscillate corresponding to the rise and decline of the groundwater elevation, where the greatest levels correspond to higher water table levels where lowest DO coincide with seasonal low groundwater levels (Figures 2.4 and 2.9). Groundwater recharge in the spring appears to introduce a large pulse of oxygen-rich water to the subsurface.

Dissolved oxygen levels present in the aerobic portion of the aquifer decrease over a 1-2 month period to stable background conditions. The amount of oxygen present within the anaerobic region undergoes a sharp increase to levels >2 mg/L during the spring recharge event, but rapidly returns to anaerobic conditions within one month presumably due to microbial consumption of oxygen during oxidation of organic contaminants. The rapid return to anoxic conditions in the petroleum impacted zone following the inflow of oxygen rich recharge water is indicative that aromatic hydrocarbon degrading bacteria are present at the Site are utilizing oxygen as a terminal electron acceptor in the metabolism of organic contaminants for cell maintenance and growth.

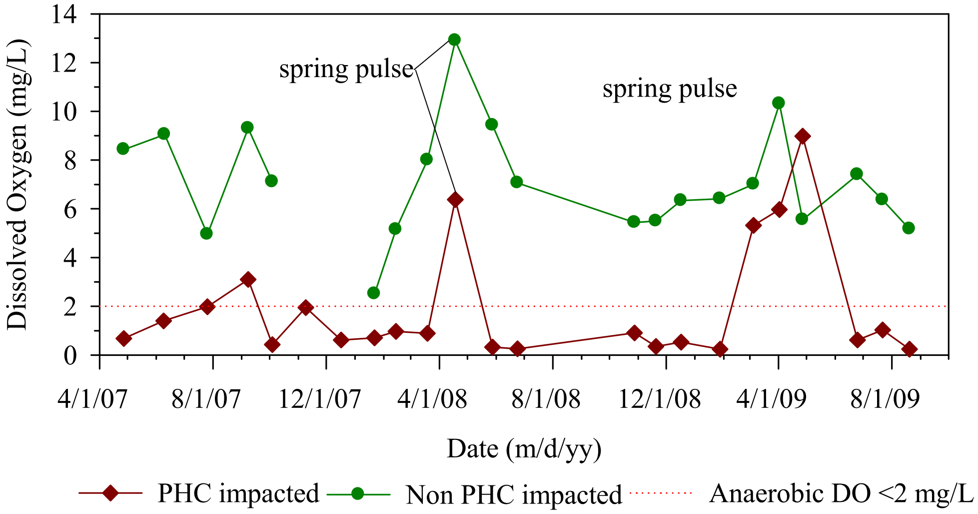

Figure 2.9: Relationship between dissolved oxygen in wells impacted with petroleum hydrocarbons (MW-103) and non-impacted by hydrocarbons (MW-12). Data from SNC-Lavalin Reports 2007-2009).

2.5.2 Alternate Electron Acceptors

Groundwater samples were collected by SNC-Lavalin from select wells and analyzed for geochemical parameters which serve as potential indicators of redox conditions: oxidation-reduction potential, dissolved oxygen, ferrous iron (Fe^{2+}), dissolved iron (Fe), dissolved manganese (Mn), nitrate (NO_3-N), sulphate (SO_4^{-2}) and dissolved methane (CH_4) from 2007 to 2010. BTEX compounds are utilized by organisms including heterotrophic aerobes, facultative anaerobes, denitrifiers, iron and sulphate reducers and fermentation bacteria (e.g. Baedecker et al., 1993; Chapelle, 2001). Dissolved NO_3^-, Fe(III), SO_4^{2-} and CO_2 act as potential terminal electron acceptors (TEA) coupled to the oxidation of hydrocarbons, where Fe(III) is present in the aquifer sediments, NO_3^- and SO_4^{2-} are supplied during groundwater recharge events or dissolution of soil gas (CO_2) (Cozzarelli et al., 1999).

A summary of geochemical information pertaining to select groundwater monitoring wells is presented in Table 2.3 corresponding to a non-petroleum hydrocarbon impacted well, MW-109 and petroleum impacted well, MW-103.

Table 2.3: Redox parameters measured from a selected non-contaminated monitoring well (MW-109) and a petroleum impacted well (MW-103)

Well ID	Date	Dissolved Oxygen	Fe^{2+}	Dissolved Fe	Dissolved Mn	NO_3-N	SO_4^{-2}	Dissolved CH_4
RDL			*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
Non-	7 Jun-07	8.0	nd	nd	nd	14	31	nd
impacted	5 May-08	11.5	nd	nd	nd	8.8	26	nd
MW-109	27 Apr-10	nm	nm	nd	nd	7.5	26	nd
PHC	7 Jun-07	1.4	4.3	8.2	0.17	nd	2	0.97
impacted	5 May-08	0.3	4.4	6.2	0.21	nd	1	0.43
MW-103	27 Apr-10	nm	nm	4.7	0.1	nd	nd	0.64

nm – not monitored, nd - non-detect, concentration less than method detection limit, units – mg/L, RDL – reportable detection limit

The geochemical results presented in Table 2.3 signify that reducing conditions exist in the petroleum hydrocarbon impacted portion of the aquifer. These findings suggest that active aerobic microbial degradation of dissolved contaminants has taken place and anaerobic biodegradation is occurring under the reduced conditions. Elevated concentrations of potential TEA's: NO_3^-, SO_4^{2-} and DO are encountered in MW-109 located outside of the petroleum impacted area and were used as background conditions. Recharge events can introduce O_2, NO_3^- and SO_4^{2-} into the reduced environment where they may become readily metabolized.

Measured concentrations of ferrous iron (Fe^{2+}) and dissolved iron, manganese (Mn^{2+}), dissolved methane (CH_4) and depleted levels of (NO_3^-), SO_4^{2-} and DO suggests the TEAs are being utilized in the petroleum impacted area (MW-103, Table 2.3). Sulphate reduction is known to accompany BTEX pollution (e.g. Chapelle et al., 1996). Increased Fe^{2+} concentrations anoxic groundwater may be produced by iron reduction by sulphide oxidation (Cozzarelli et al., 1999). The reduction of Fe-oxides leads to an increase in Fe^{2+} concentration. When sulphate is reduced, iron sulphide precipitates resulting in a decrease in Fe^{2+}. Iron reducing (IRB) and sulphate reducing bacteria (SRB) have been indentified in both aerobic and anaerobic zones of the aquifer determined by microbial groundwater sampling conducted by SNC-Lavalin and analyzed by Maxxam Analytics. The presence of dissolved metals Mn^{2+} and Fe^{2+} occur in environments depleted in oxygen, levels < 2 mg/L, which is consistent with what is observed in the PHC impacted anaerobic zone. Decrease in sulphate and nitrate concentrations at groundwater monitor MW-103 screened in the anaerobic aquifer is an indication that the compounds may be serving as electron acceptors for the microbial degradation of petroleum compounds.

Dissolved oxygen levels measured in multilevel wells MW-301 and MW-302 located in the source zone following the spring recharge event in April 2009 do not indicate the short term presence of oxygen-rich recharge waters. The depleted oxygen levels in the aquifer, <1 mg/L, may be indicative of a higher dissolved oxygen demand located in the source zone where oxygen is readily consumed in the metabolism of organic contaminants than compared to MW-103, located on the fringe of the contaminant plume. The vertical and spatial distribution of limited amounts of potential TEA, DO and NO_3^- present within the study area is presented in Figure 2.10 below and Table A.6 in Appendix A. Depleted DO levels occur simultaneously with reduced NO_3^- concentrations.

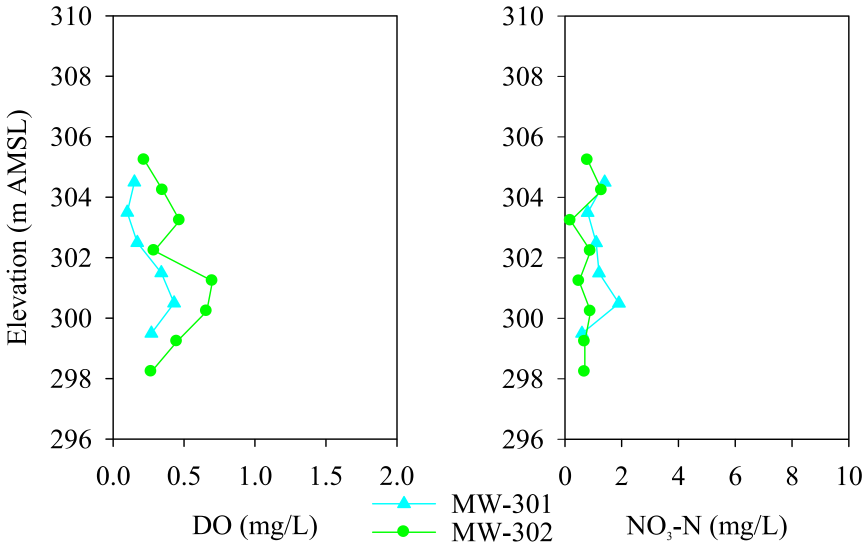

Figure 2.10: Distribution of dissolved oxygen (a) and nitrate as total nitrogen (NO_3-N) (b) in multilevel wells MW-301 and MW-302 located within the source/residual zone.

2.5.3 Evidence of Natural Attenuation

The geochemical results indicate that naturally occurring TEAs dissolved oxygen, nitrate and sulphate concentrations are depleted within the contaminant plume compared to the background conditions at the Site. Measurements indicating the production of Fe^{2+} and the presence of CH_4 formed in the final stages of the reductive sequence in the anaerobic aquifer also provide evidence to suggest that natural attenuation is occurring at the Site. Considering the presence of NAPL within the source zone, the contaminant plume has undergone limited spreading and there is evidence to suggest that the plume is decreasing in size based on historic groundwater quality sampling conducted by SNC-Lavalin. The absence of DO and NO_3^- in MW-103 (Table 2.3) from background conditions (MW-109) indicate that redox conditions exist in the PHC impacted zone (MW-103), whereby anaerobic bacteria are active at redox level typical for sulphate and nitrate reduction (Atcon & Barker, 1992).

Further evidence to suggest that indigenous microbes are actively degrading aromatic hydrocarbons present in the subsurface is presented in Figure 2.11, where a general trend of declining aqueous concentrations of individual contaminants of interest benzene, toluene, ethylbenzene and total xylenes in monitoring well MW-103 is depicted. The removal of BTEX contaminants from MW-103 can be attributed to aquifer advection, dispersion and diffusion, loss of volatiles in the unsaturated zone and natural attenuation by microbial populations utilizing naturally occurring TEAs to biodegrade the aromatic hydrocarbons.

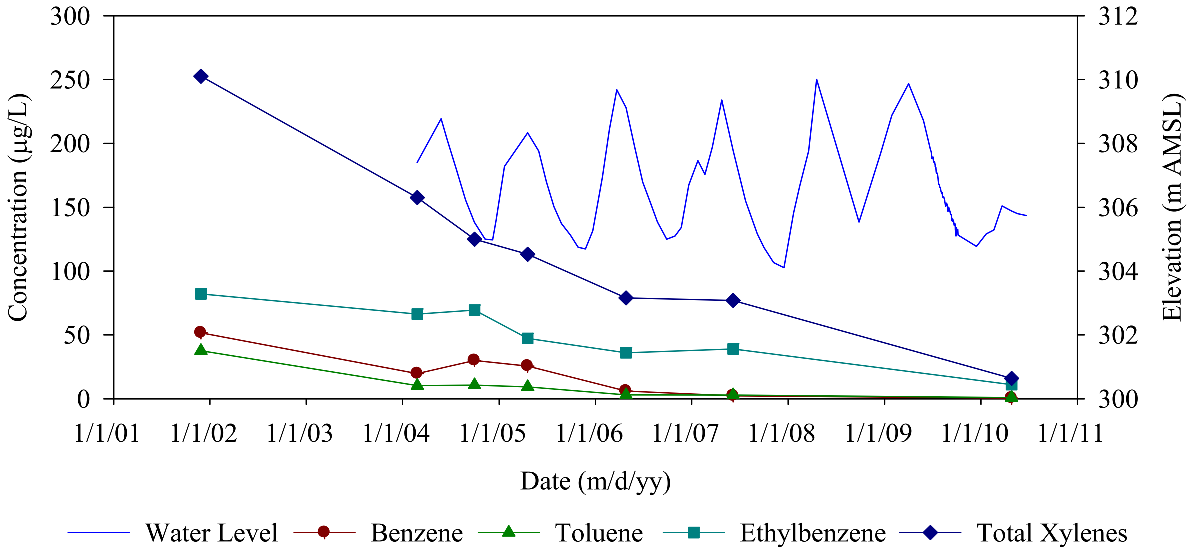

Figure 2.11: Seasonal groundwater elevations and measured concentrations of benzene, toluene, ethylbenzene and total xylenes between 2001 and 2010 at MW-103 (SNC-Lavalin, 1999-2010).

2.6 Physical Aquifer Characterization

Subsurface heterogeneities play an important role in the transmittance of groundwater, the distribution of contaminants and subsequently the delivery of remediation treatments to targeted areas of the subsurface. Physical properties of the aquifer materials including hydraulic conductivity (K), porosity (n), groundwater velocity (v), longitudinal dispersivity (α_L) and hydrodynamic dispersion (D) were determined to evaluate the effect of heterogeneities on groundwater flow and the distribution of residual petroleum hydrocarbon sources of contamination. Field and lab testing were conducted in order to estimate aquifer hydraulic parameters included slug testing, single-well point dilution test, falling-head permeameter test and grain size analysis, while a 1D advection-dispersion solution was applied to single-well point dilution field data.

2.6.1 Conventional Slug Test

Hydraulic conductivity was estimated using rising and falling head slug tests conducted in the injection well, MW-501, at various time in order to assess groundwater flow conditions prior to and following the series of large volume remedial solution injections. The bulk hydraulic conductivity estimate is representative of a 3.2 m interval across Unit 3 and Unit 4 consisting of a sand and gravel and sand materials. Field estimates of hydraulic conductivities were determined using the Hvorslev (1951) analysis as presented in the following equation (2.1):

$$K = \frac{r^2 \ln\left(\frac{L}{R}\right)}{2LT_o} \tag{2.1}$$

Where:

r– radius of well casing (L);
R – radius of sand pack (L);
L – length of sand pack (L);
T_o – time required 37% water level rise of the initial change, obtained from graph of H/H(0)

Pre-Injection

The bulk hydraulic conductivity of the targeted aquifer materials was determined by performing a series of rising-head slug tests in injection well MW-501 on July 28th, 2009 following well development. The bulk average hydraulic conductivity of the aquifer material was estimated to be 2.5×10^{-6} m/s ($\sigma = 3.0 \times 10^{-7}$ m/s) using the Hvorslev (1951) solution. A detailed summary of the test analysis and complete results are presented in Appendix A, Table A.7.

Post-Injection

In situ field tests in injection well MW-501 were conducted to assess the bulk hydraulic conductivity of the aquifer materials following 12 consecutive remedial solution injections. A series of falling-head tests were conducted on November 8th, 2009 by using 1-4 L volume slugs resulting in a hydraulic conductivity of 4.3×10^{-6} m/s ($\sigma = 1.4 \times 10^{-6}$ m/s). The hydraulic conductivity was also estimated using falling-head data retrieved from the data logger on November 18th, 2009 following the injection number 12 which yielded a hydraulic conductivity estimate of 6.4×10^{-6} m/s. The permeability of the sandy unit screened along the injection interval measured 22% greater following the injection activities, which would have served to further develop and improve well efficiency.

Aquifer parameters were also inferred from the reverse pump test data obtained during the injection of a large volume of tracer test solution on November 18th, 2009. Water levels of select wells were monitored using water level tapes and/or pressure transducers during the injection and up to 24 hours following the completion of the injection solution.

The application of the Theis Method is not always applicable to unconfined aquifers due to the delay in releasing water from storage, however the Theis Method was used for this situation as the amount of groundwater mounding was less than 10% of the assumed saturated pre-injection aquifer thickness of 15-20 m (Kelly & Carter, 1993). In an ideal setting the Theis Method would be applied to the unconfined aquifer using the late time data where the lag associated with pore gravity drainage had ceased, which is often greater than 100 minutes of pumping. However, due to the short duration of the injection phase (63 minutes), the intermediate time data were used in the estimation of bulk aquifer transmissivity and storage values. The use of intermediate time pump data may result in the underestimate of aquifer parameters because of the lag in water being released from storage slow gravity drainage or soil pores (Shwartz & Zhang, 2003). The results of the field data are consistent with the notion that intermediate segment data are often characterized by a flat curve where the gravity water approaches the saturation zone, but is not yet in equilibrium with the saturated flow (Kresic, 2007).

Bulk hydraulic conductivity, storativity and transmissivity values were inferred from analysis of reverse pump test data obtained in downgradient wells MW-401-4 and MW-402-4 screened at the water table. The drawdown used in the analysis was assumed to be equivalent to the amount of water table mounding that occurred during the injection phase and the well was assumed to be fully penetrating.

The bulk transmissivity, T and bulk storativity, S of the unconfined aquifer were determined by applying the Theis curve fitting method to the intermediate time data between 5 and 63 minutes by the following equations (2.3a) and (2.4) in addition to the recovery data (2.3b):

$$T = \frac{Q\omega(u)}{4\pi s} \tag{2.3a}$$

$$T = \frac{2.3Q}{4\pi\Delta s'} \tag{2.3b}$$

$$S = \frac{4uTt}{r^2} \tag{2.4}$$

where log drawdown s versus log time t field data was superimposed on the log well function plot $\omega(u)$ versus log 1/u to obtain a match point to the intermediate time data of the parameters of interest which were applied in equations (2.3a) and (2.4) and $\Delta s'$ is the change in residual drawdown over one log cycle (t/t′) as applied in equation (2.3b). Curve matching software AquiferWin 32® was used to estimate the best-fit bulk transmissivity and storativity values, which are presented in Table 2.4, with a summary of the analyses presented in Appendix A. The bulk hydraulic parameters estimated during the injection and recovery periods, yielded average values of 0.02 and 32 m^2/day for storativity and transmissivity, respectively.

Table 2.4: Summary of bulk aquifer parameters transmissivity and storativity estimated from injection 12 using various analytical methods.

Well ID	Method	Bulk Transmissivity (m^2/s)	Bulk Storativity
MW-401-4	Recovery	3×10^{-4}	--
	Theis, 1935	4×10^{-4}	0.02
MW-402-4	Theis, 1935	5×10^{-4}	0.02
	Recovery	2×10^{-4}	--
MW-501	Theis, 1935	2×10^{-5}	--
	Neuman Partial	1×10^{-4}	--

Transmissivity for an unconfined aquifer can also be represented by equation (2.5) as a function of hydraulic conductivity, K and saturated aquifer thickness, b, however it is not as well defined as in a confined aquifer (Freeze & Cherry, 1979):

$$T = Kb \tag{2.5}$$

Applying equation (2.5) and assuming the saturated thickness of the overburden aquifer is 15 m based on the assumed bedrock elevation and hydraulic conductivity of the MW-501 test interval is 6.4×10^{-6} m/s, a bulk transmissivity value of 1×10^{-4} m^2/s, equivalent to 8.6 m^2/day is inferred. The estimated bulk transmissivity value determined using equation (2.5) is less than the field measured transmissivity value from the results of the pumping test, as presented in Table 2.4.

For unconfined aquifers, the storativity value is equal to the specific yield S_y and ranges between 0.01 and 0.30 related to dewatering of soil pores by gravity drainage (Freeze & Cherry, 1979). Storativity values estimated for the sand and gravelly sand units are within the expected range for these unconsolidated materials (Freeze & Cherry, 1979). Under ideal conditions, late time data consisting of periods greater than 100 minutes would be used to Theis curve match parameters where aquifer recharge and saturated flow have achieved equilibrium as a result of the injection (Kresic, 2007).

The observed changes in groundwater elevation throughout the injection phase fit well with the Theis curve to approximate parameters of interest, despite use of intermediate time data in the analysis. Late time data is ideal in the estimation of bulk hydraulic parameters as the effects of elastic storage which set in after pumping is initiated have dissipated. Pumping tests in unconfined aquifers must be carried out for a long duration until steady state is reached, where early time data are valid, however data changes due to de-watering of pore spaces which is time-lagged. A reverse pumping test resulted in water table mounding in the vicinity of the injection well, accompanied by changes in the vadose zone which becomes temporarily saturated during the injection phase.

2.6.2 Single-Multilevel Well Point Dilution Test

A series of single-well point dilution tests, referred to as natural gradient tests were conducted in multilevel well MW-301 in select ports screened over various aquifer materials in order to assess the vertical distribution of hydraulic conductivity within the aquifer following the procedure described by Halevy et al. (1967) and Drost et al. (1968). The multilevel wells were comprised of 0.00635 m ID low-density polyethylene tubing containing a 0.20 m screened interval from an elevation of 304.5 to 299.5 m AMSL spaced 1 m apart to derive hydraulic conductivity estimates within various stratigraphic formations.

Natural gradient tests in MW-301-7 and MW-301-12 took place on May 21st, 2009, followed by tests in MW-301-8, MW-301-9, MW-301-10 and MW-301-11 on May 22nd, 2009. The test solution consisted of purged petroleum impacted groundwater collected from on-Site wells and amended with a conservative tracer bromide (as sodium bromide, NaBr) to a concentration of 100 mg/L bromide (Br^-). The prepared solution was mixed and re-injected into the designated multilevel port at a rate between 1-1.3 L/min.

A 25 mL groundwater sample was collected in a plastic scintillation vial once the injection was complete, in order to establish the tracer concentration in the well at time 0. Groundwater samples were collected from the well ports every 5-10 min and subject to natural gradient drift between 2.3 and 5.8 hrs (140 and 350 min) following the end of the injection. Groundwater samples were analyzed for the presence of bromide tracer at the University of Waterloo Organic Geochemical lab at room temperature.

Br^- breakthrough curves were prepared for each multilevel port, in which Darcy velocity (q) and hydraulic conductivity was estimated assuming a hydraulic gradient of 0.01 based on May 2008 monthly monitoring data and a mean effective porosity of 0.32, determined from analysis of aquifer materials as described in Section 2.6.3.

The Darcy velocity for the different sections of the aquifer materials was evaluated from the measured concentration values using the Drost and Neumaier (1974) equation (2.6) as follows:

$$q = \frac{W}{\alpha A t} \ln \frac{C_o}{C} \tag{2.6}$$

Where

q - Darcy flux or apparent velocity inside well (m/s);
W - volume of fluid in test section (m^3)
A - cross-sectional area normal to the direction of flow (m^2);
t - time when concentration is equal to C (s);
C_o - tracer concentration at $t = 0$ (mg/m^3);
C - tracer concentration at time = t (mg/m^3);

α - borehole distortion factor of 2 for an open well (-).

The cross-sectional area was estimated based on assuming radial flow of the test solution from the screen into the porous medium, where A is determined by equation (2.7):

$$A = \pi \mathrm{rh} \tag{2.7}$$

Where:

r - well radius (0.004 m);
h - length of tested section in the borehole (0.2 m)

The volume of fluid in the test section, W is determined from equation (2.8):

$$W = \pi r^2 h \tag{2.8}$$

The summary of hydraulic conductivity, K and groundwater velocity, v estimates corresponding to the multilevel ports situated in various stratigraphic units is presented in Table 2.5.

Table 2.5: Summary of hydraulic conductivity and average groundwater velocities estimated from single-well dilution tests conducted within various intervals of the screened aquifer [method from Drost & Neumaier (1974)]

Well ID	MW-301-7	MW-301-8	MW-301-9	MW-301-10	MW-301-11	MW-301-12
Depth (m AMSL)	304.5	303.5	302.5	301.5	300.5	299.5
K (m/s)	$1.5\text{x}10^{-4}$	$1.2\text{x}10^{-6}$	$1.0\text{x}10^{-4}$	$7.2\text{x}10^{-6}$	$3.7\text{x}10^{-6}$	$9.3\text{x}10^{-5}$
v (m/day)	0.43	0.03	0.29	0.02	0.01	0.26
Unit	3	4	4	5	5	5
Sediment Description	Sand and Gravel	Sand with Fines	Sand and Gravel	Sand with Fines	Sand with Fines	Sand and Gravel

Analysis of Single-Point Dilution Data Using PULSEPE

Average linear groundwater velocity and subsurface dispersivity values were estimated at discrete vertical depths within multilevel well MW-301 by fitting Br^- tracer data obtained from individual single-well point dilution tests to a 1D advection-dispersion equation developed by Gierczak et al. (2006). The equation assumes the delivery of the tracer solution as a pulse containing a finite source width utilizing equations (2.8) and (2.9) as described by Devlin & Barker (1996) and Gierczak et al. (2006):

$$C(x,t) = \frac{C_o}{2}\left[\operatorname{erfc}\left(\frac{x - \frac{w}{2} - vt}{2(Dt)^{1/2}}\right) - \operatorname{erfc}\left(\frac{x + \frac{y}{2} - vt}{2\left[D(t - \frac{w}{v})\right]^{1/2}}\right)\right] \tag{2.8}$$

$$D = v\alpha_L + D^* \tag{2.9}$$

Where:

C_o - the concentration of the tracer injected (mg/L);
x – distance from the source (m);
w – source width (m);
D – dispersion coefficient (m^2/s);
t – time (s);
v – average linear groundwater velocity (m/s);
α_L – longitudinal dispersivity (m);
D^* - effective diffusion coefficient (m/s)

Tracer test breakthrough data was inputted into PULSPE model with initial estimate parameters; $v = 2.5\times10^{-6}$ m/s, $\alpha_L = 0.038$ m, w = 0.01 m, x = 0.025 m and $D^* = 1\times10^{-8}$ m/s. The location of the injection well was the same as the source, however the distance of the well from the source was assumed to be 0.025 m in order to apply the model to the data set. The results of the best-fit PULSPE model to the field data are presented in Figure 2.12 and Table 2.6 while data are presented in Appendix A Table A.8.

Average linear groundwater velocity, hydrodynamic dispersion and longitudinal dispersivity estimates were determined for aquifer materials screened within MW-301-7, MW-301-9, MW-301-12 using PULSEPE to find a best-fit solution. The model did not converge for MW-301-8, MW-301-10 and MW-301-11 screened across lower conductive units.

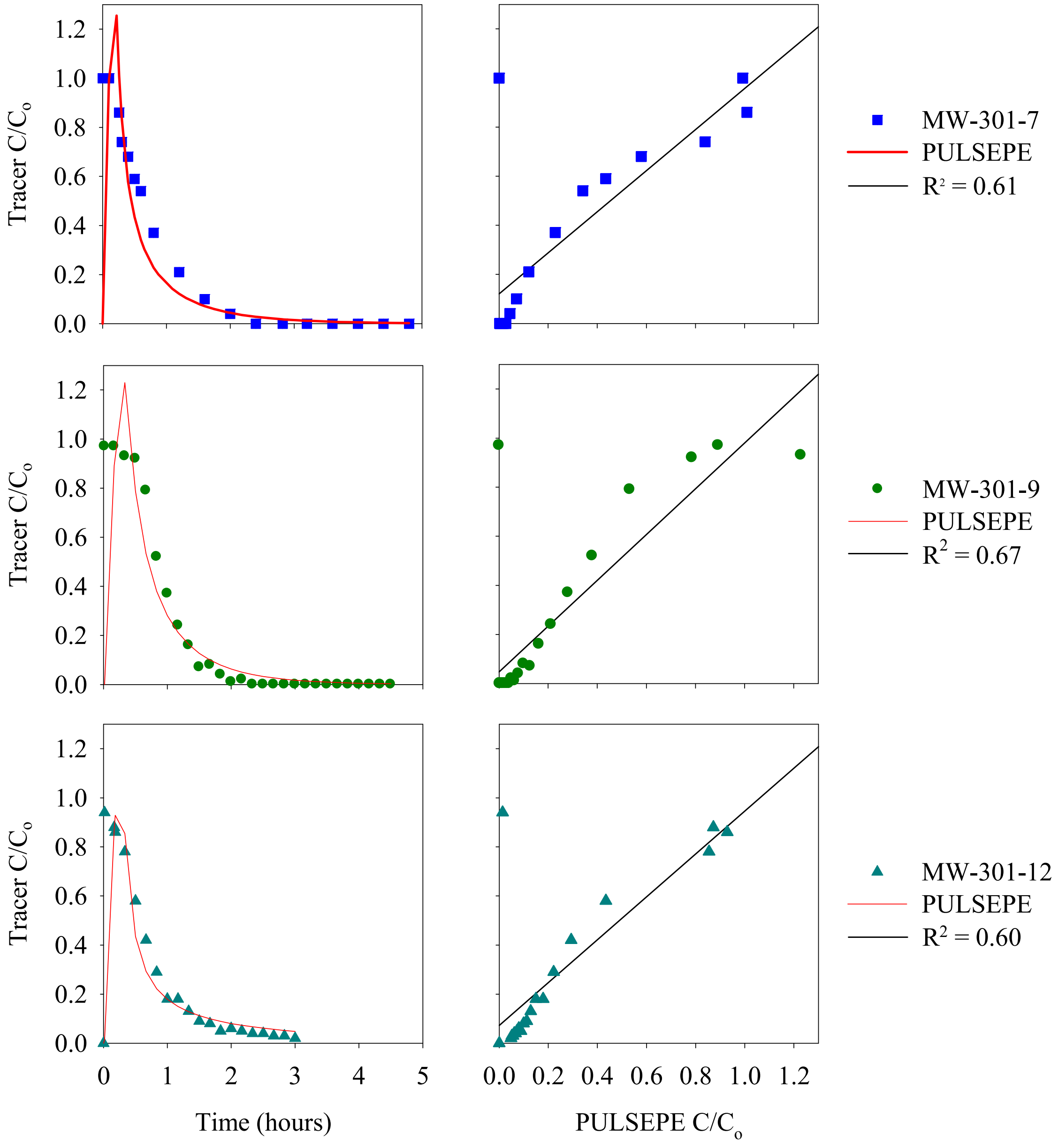

Figure 2.12: Comparison of observed single-point dilution and best-fit PULSEPE modeled (Devlin, 2005) breakthrough curves (left) from MW-301 ports 7,9 + 12.

Table 2.6: Summary of best-fit PULSPE 1D advection-dispersion solutions corresponding to observed bromide tracer breakthrough within select multilevel ports of MW-301.

Well ID	MW-301-7 (Unit 4)	MW-301-9 (Unit 4)	MW-301-12 (Unit 5)	Arithmetic Mean
Depth (m AMSL)	304.50	302.50	299.50	--
v (m/day)	1.6	1.2	0.9	1.3
α_L (m)	0.02	0.01	0.04	0.02
D (m^2/day)	0.03	1.2	3.8	1.7
95% C.I v (m/s)	1.20 to 2.59	0.86 to1.64	0.58 to 2.16	--
95% C.I α_L(m)	0.008 to 0.068	0.005 to 0.032	0.01to 1.04	--

No solution for MW-301-8, MW-301-10 or MW-301-11: PULSEPE model did not converge.
v – average linear groundwater velocity, α_L – longitudinal dispersivity, D – calculated hydrodynamic dispersion coefficient, D = α_L+ D*,
No solution – PULSEPE model did not converge

Average linear velocity estimates using PULSPE varied between 0.9-1.6 m/day and were greater than those determined using Drost & Neumaier (1974) analysis. The PULSPE solution most likely provided an overestimation of average linear velocity due to aquifer heterogeneities and local variations in flow. Advection is an important transport process at the Site due to the relatively permeable aquifer materials in addition to dispersion. Estimates of longitudinal dispersivity values of sand and gravel units ranged from 0.01 to 0.04 m and were determined within direct proximity to the source showing relatively limited dispersion. Low reliability longitudinal dispersivity estimates the aquifer materials are often associated with small-scale estimates (< 3m) (Gelhar et al., 1955-1974, 1992). Longitudinal dispersion is a function of scale and will increase further away from the source due to large-scale heterogeneity until it eventually reaches a constant (Shwartz & Zhang, 2001). Although the PUSLEPE model may have overestimated the average linear groundwater velocity within select zones of the aquifer, it was useful in determining the variability in longitudinal dispersion in two separate sand and gravel units.

2.6.3 Grain Size Analysis

Hydraulic conductivity of the aquifer materials was estimated using grain size analysis empirical solutions developed by Hazen (1892), Schlichter (1905), and Kozeny-Carman which was first developed by Kozeny (1927) and modified by Carman (1937, 1956). The Hazen, Schlichter and Kozeny-Carman empirical methods were used to estimate hydraulic conductivity based on estimates similar to falling head permeameter testing and field slug tests.

The Schlichter and Kozeny-Carman empirical methods were selected as part of estimating the vertical distribution of hydraulic conductivity in the subsurface based on formulae yielding similar results to more appropriate falling head permeameter testing conducted on select soil samples. The hydraulic conductivity of each soil sample was taken to be the Kozeny-Carman value and when appropriate the arithmetic average between both empirical methods was used. A detailed summary of grain size analysis procedure and the horizontal hydraulic conductivity estimates for each borehole obtained from every sediment sample is presented in Table A.10 of Appendix A.

The vertical distributions of hydraulic conductivity for boreholes BH-401, BH-402, BH-403, BH-405, BH-406 and BH-501 are presented in Figure 2.13. An average hydraulic conductivity of 2.4×10^{-2} m/s was estimated for a gravel unit located in BH-406 8.4-9 m bgs (elevation 301.9 – 302.5 m AMSL). An average hydraulic conductivity of 1.6×10^{-7} m/s was calculated for gravelly silty sand in BH-402-5 4.6-5.3 m bgs (elevation 305.79 – 306.49 m AMSL). A summary of the hydraulic conductivity estimated from grain size analysis for each borehole is presented in Table 2.7.

Table 2.7: Summary of average hydraulic conductivity estimates using Kozeny-Carman and Schlitchter empirical solutions for select boreholes.

Borehole ID	Depth Interval Sampled (m AMSL)	Geometric Mean K (m/s)	Variance K log Cycle	Mean Groundwater Velocity (m/day)	Min K (m/s) Soil Type	Max K (m/s) Soil Type
BH-501	305.68 - 302.87	7.4x10^{-6}	5.01	0.004	1.4x10^{-6} silty SAND	3.1x10^{-4} Sandy GRAVEL with grace silt
BH-401	309.20 – 301.27	1.0x10^{-5}	0.95	0.005	7.7x10^{-7} SAND with some silt and gravel	3.6x10^{-3} Gravelly SAND with trace silt
BH-402	307.66 – 301.57	9.4x10^{-6}	0.81	0.004	2.2x10^{-7} Gravelly silty SAND	7.0x10^{-4} Sandy GRAVEL with trace silt
BH-403	307.28 – 301.41	1.8x10^{-6}	0.91	0.001	2.8x10^{-7} Gravelly SAND with some silt	6.7x10^{-4} SAND with trace gravel and silt
BH-405	306.27 – 302.04	2.1x10^{-6}	0.69	0.003	3.4x10^{-7} Silty SAND with trace gravel	1.7x10^{-5} GRAVEL and SILT with some sand
BH-406	308.24 – 301.84	8.0x10^{-6}	1.05	0.01	4.9x10^{-7} silty GRAVEL with some sand	3.4x10^{-3} GRAVEL with some sand and trace silt

The heterogeneity of the aquifer materials is reflected in Figure 2.13, where the hydraulic conductivity can vary three orders of magnitude for distinct layers within a 0.1 m interval and two orders of magnitude between distinctly different sediment types for boreholes BH-501, BH-401, BH-402, BH-403, BH-405 and BH-406 equipped with screened intervals to serve as monitoring wells.

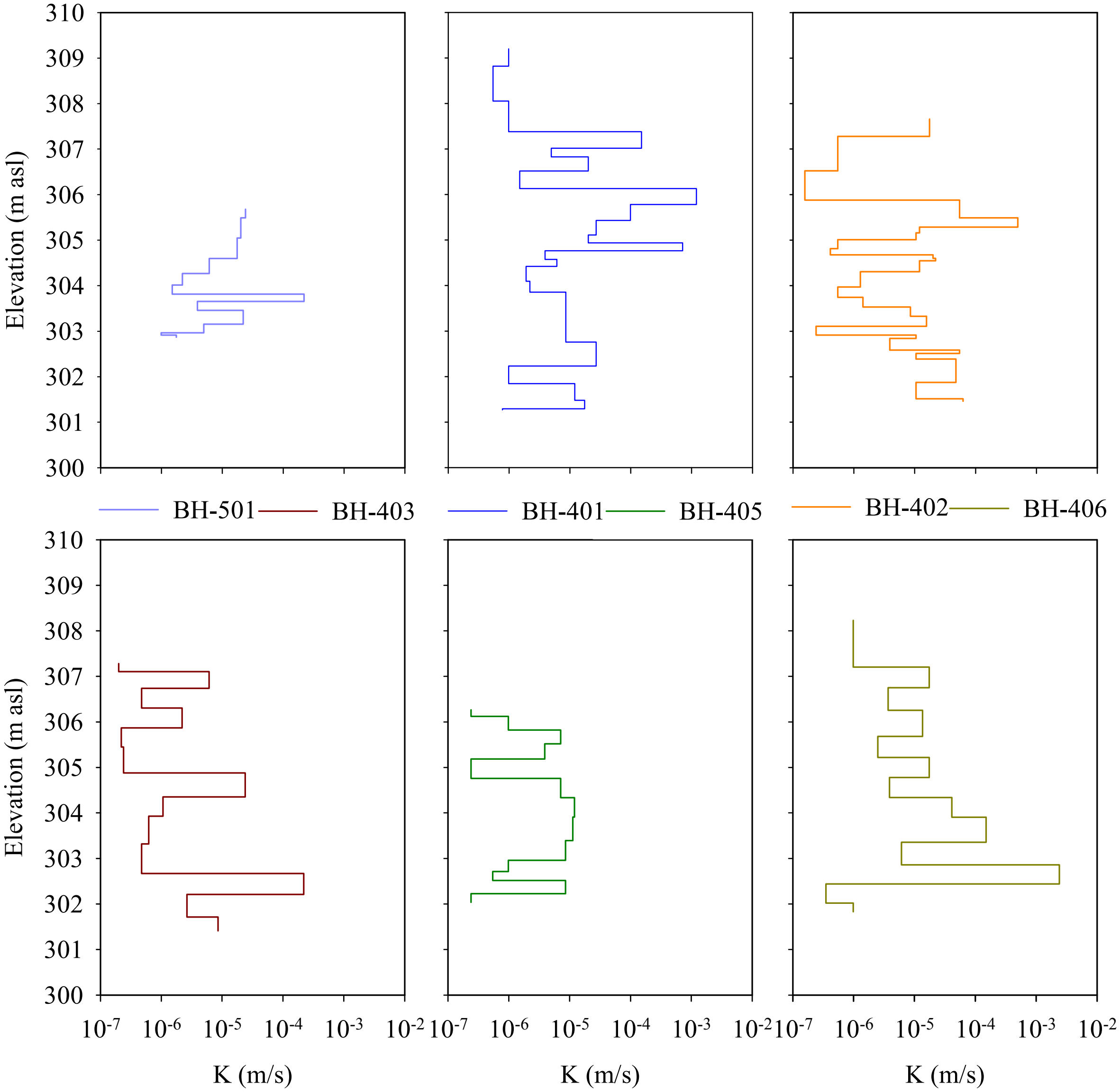

Figure 2.13: Vertical and spatial distribution of horizontal hydraulic conductivity estimated from grain size analysis empirical formulae (average Schlichter + Kozeny-Carman).

Silty units are generally less permeable compared to gravelly units. Hydraulic conductivity estimates using empirical methods yield a variance of 1.00 and standard deviation of $5.8\text{x}10^{-4}$ for the 93 samples collected from 6 borehole locations. Schulze-Makuch et al. (1999) describes a geological unit to be heterogeneous when the variance of K measurements exceeds 0.5 log cycles, which provides evidence to support the heterogeneous description of the aquifer materials present in the study area. The variance calculated for each individual borehole presented in Table 2.9 indicates that the aquifer materials are statistically heterogeneous, as the minimum variance obtained was 0.69 for BH-405, which is consistent with observations of core retrieved in the field. Groundwater flows parallel to the layering of the stratigraphic units, whereby K was estimated for particular geological layers using the arithmetic mean equation (2.10):

$$K = \sum \frac{K_i d_i}{d} \tag{2.10}$$

Where d is the total thickness of aquifer materials under investigation, d_i is the thickness and K_i is the hydraulic conductivity of the particular unit of interest. The results of the average weighted hydraulic conductivity estimates for stratigraphic units 1 through 5 consisting of fill (1), sand (2), sand and gravel (3), sand (4), sand and gravel (5) are illustrated in Figure 2.14.

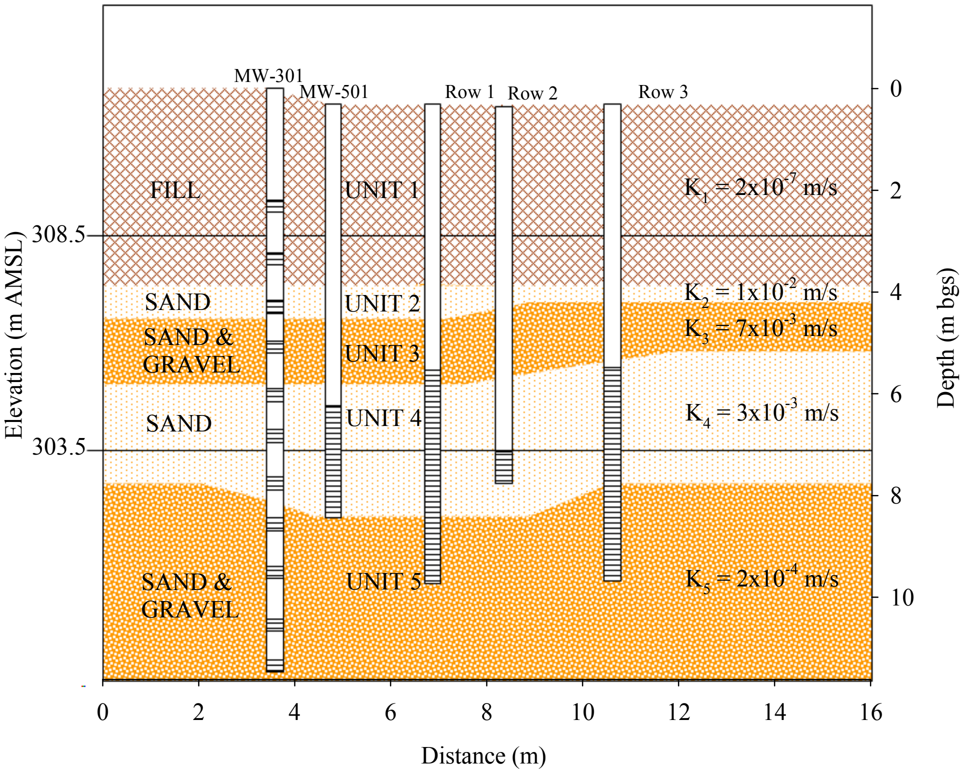

Figure 2.14: Conceptual geologic cross-section of the research Site within the selected study area depicting the 5 stratigraphic units present from east to west inferred from coring activities and weighted average hydraulic conductivity assigned to each unit as determined from grain size analysis.

2.6.4 Falling-Head Permeameter Test

The falling-head permeameter test was performed to estimate the saturated hydraulic conductivity for select sediment samples, from boreholes, following the test procedure developed by Oldman (1998). The hydraulic conductivity of the saturated material is estimated from the following equation (2.11) developed after Todd (1959):

$$K = \frac{aL}{At} \ln\left(\frac{H_o}{H_l}\right) \tag{2.11}$$

where a is the cross-sectional area of the column which falls from the initial head H_o to H_l during a timed interval t, A is the cross-sectional area of the soil column and L is the length of the soil sample. The hydraulic conductivity estimated using the falling head permeameter in the laboratory setting was subject to a 1.34 correction factor to account for temperature differences between the lab (approximately 20°C) and the mean average annual groundwater temperature at the Site (10°C). The correction temperature dependent parameters fluid viscosity μ and density ρ are governed by the equation (2.12) for hydraulic conductivity, K:

$$K = \frac{k\rho g}{\mu} \tag{2.12}$$

where k is the permeability of the sediment and g is the acceleration due to gravity. The permeability of each sample was not calculated; however the relationship between fluid viscosity and density was used to adjust the hydraulic conductivity to groundwater flow conditions at 10^{o}C. Hydraulic conductivity determined by the falling-head permeameter method ranged from $2\text{x}10^{-4}$ to $5\text{x}10^{-7}$ m/s. Data and complete results of the falling head estimates of the saturated hydraulic conductivity are presented in Table A.11 of Appendix A. Falling head permeameter tests were limited to 17 of the 114 soil samples collected throughout the drilling activities, which were primarily composed of sand with less than 35% gravel and silt constituents. Samples with very fine materials that were lost or containing large proportions of gravel prevented adequate packing of the soil column. Falling head permeameter test details including sediment descriptions are presented in Table A.11. Only samples which had effective grain size diameter, d_{10} larger than 0.0625 mm were selected for permeameter testing such as sand, silty sand and gravelly sand.

Hydraulic conductivity estimates determined by permeameter testing were compared to empirical formulae determined by grain size analysis shown in Figure 2.15, using linear regression statistical analysis with a 95% confidence envelope.

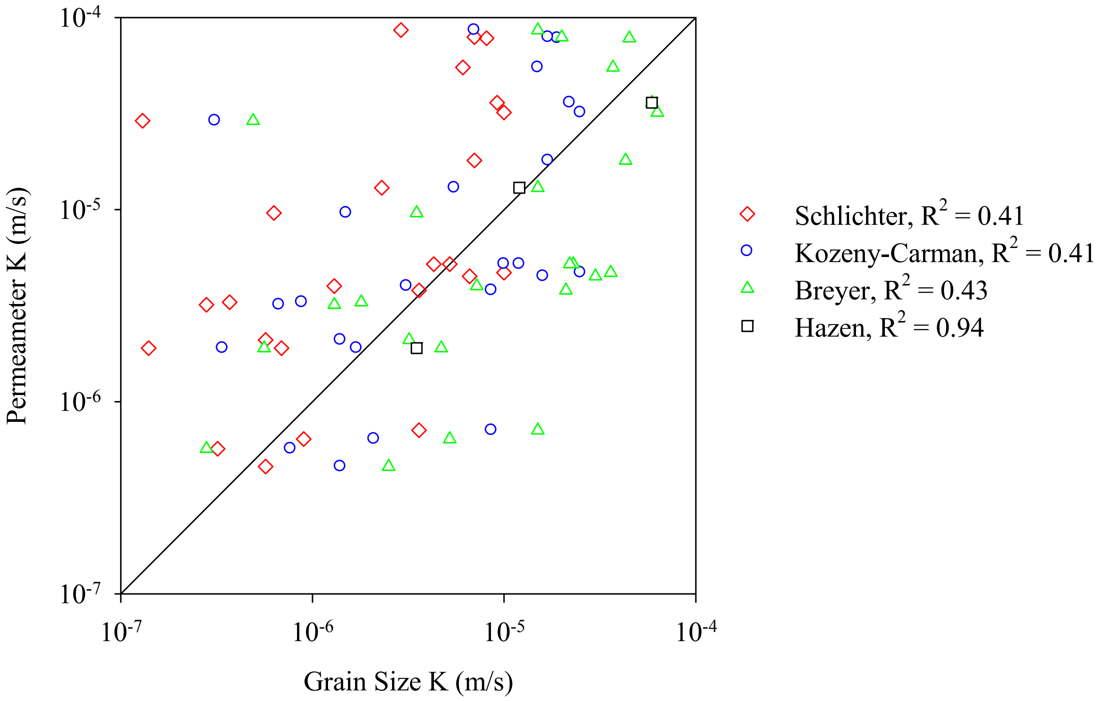

Figure 2.15: Comparison of hydraulic conductivity, K (m/s) estimates of sediment samples using grain size analysis and empirical formulae and falling-head permeameter testing. Hazen method correlated well with permeameter results, however the analysis is not valid for the majority of samples since the uniform coefficient, U > 5.

The Hazen empirical method had the highest correlation ($R^2 = 0.94$) to the permeameter estimates of hydraulic conductivity, followed by Breyer ($R^2 = 0.43$), Kozeny-Carman ($R^2 = 0.41$) and Schlichter ($R^2 = 0.41$). Although the Hazen analysis was well correlated to the permeameter testing, the majority of the sediments sampled were poorly sorted with a uniformity coefficient greater than 5, which does not meet the requirements for the Hazen analysis to be valid resulting in an average K comprised of Kozeny-Carman and Schlichter methods being preferred over the other methods. The

Schlitchter method had a tendency to underestimate the hydraulic conductivity values compared to falling-head permeameter testing. Kozeny-Carman and Breyer empirical analyses had an equal tendency to either over or underestimate K compared to permeameter results. Hydraulic conductivities estimated from permeameter falling-head tests typically are more representative of in situ hydraulic conductivities compared to grain size analysis because a larger sample of aquifer material is being investigated. Hydraulic conductivity increases with scale of measurement in heterogeneous media (Schulze-Makuch et al., 1999) and unconsolidated sediments (Herzog & Morse, 1984; Bradbury & Muldoon, 1990).

2.7 Site Characterization Summary

A detailed investigation of the physical and geochemical aspects of the hydrogeological setting of the Site was conducted in order to effectively design, implement and evaluate the delivery of a remedial solution to targeted areas of the aquifer. Historic information pertaining to the hydrogeologic flow regime and groundwater quality provided by SNC-Lavalin Inc. was useful in characterizing the aquifer and identifying a target study area. Additional subsurface investigations carried out as part of the research project provided further details pertaining to the transport of groundwater and contaminants. The results of the geochemical investigation were applied to the design phase of an in situ remediation system in order to stimulate biodegradation of aromatic hydrocarbons. There is field evidence to suggest indigenous microbial populations are readily utilizing naturally occurring terminal electron acceptors present in the subsurface such as dissolved O_2, NO_3^- and SO_4^{2-} in the biodegradation of aromatic hydrocarbons as the TEAs are present in depleted amounts compared to the background, non-petroleum hydrocarbon impacted aerobic zone of the aquifer. Design and delivery of the remediation system will be discussed in further detail in Chapter 5.

Chapter 3: Characterization of Subsurface Contaminants

3.1 Origin of Contaminants in the Subsurface

Groundwater and soil contamination at the Site originated from leaky underground storage tanks (LUST) releasing light non-aqueous phase liquid (LNAPL) petroleum products into the subsurface. LNAPL compounds are less dense then water and have a tendency to float on top of the capillary fringe. The historical period of release of petrochemicals from the USTs is unknown, however, the Site operated for 50 years prior to the tanks and infrastructure being removed in 1999 as part of the decommissioning procedure.

During a spill event, LNAPL flows by gravity downward through the unsaturated zone until it reaches residual saturation and is retained by capillary forces or is transported further downward to the saturated zone boundary referred to as the capillary fringe. Upon arrival at the capillary fringe, the NAPL will spread out laterally as it pools at the interface, changing the wetting properties of water and causing the capillary fringe to collapse. Dissolution of NAPL leads to the migration of dissolved phase contaminants in the groundwater system which is subject to retardation by the constant dissolution-adsorption-dissolution processes occurring in the smear zone (Mose & Mushrush, 2000).

The spatial distribution of LNAPL in the subsurface is influenced by the volume and chemical composition of the NAPL as well as hydrogeological properties of the subsurface materials. Vadose zone and aquifer heterogeneities, location of the capillary fringe and the hydrogeological flow regime present at the Site also play an important role in the transport of NAPL in the subsurface.

3.2 Nature of the Contaminants

Gasoline is comprised of over 150 separate compounds (Domask, 1984; Mehlman, 1990) consisting of 20-50% aromatic hydrocarbons, 4-8% alkanes, 2-5% alkenes, 25-40% isoalkanes, 3-7% cycloalkanes, and 1-4% cycloalkenes (IARC, 1989). Contaminants of concern within gasoline mixtures have been identified based on their toxicity and carcinogenicity (Mehlman, 1992). The United States Environmental Protection Agency (EPA) identifies gasoline constituents of particular interest which include the aromatics that predominantly partition into the aqueous phase: benzene, toluene, ethylbenzene, xylene isomers (m,p-xylene and o-xylene) and are referred to as the BTEX compounds. These chemicals are volatile, readily soluble, and persistent in groundwater. BTEX compounds are subject to soil and water quality standards as they are often used to evaluate the risk associated with a contaminated area. Additional gasoline constituents of concern include naphthalene and the trimethylbenzene isomers: 1,3,5-trimethyl benzene, 1,2,4-trimethyl benzene, 1,2,3-trimethyl benzene. The group of these chemicals will be referenced as BTEXTMB from here on out. The pertinent physical-chemical properties of these compounds, which influence the fate of the compound in the environment, are presented in Table 3.1.

Table 3.1: Summary of chemical properties for the individual gasoline constituents.

Component	MW [g/mol]	S_i^{sat} [mg/L]	P_i [atm]	k_H [-]	*Log K_{ow}*	K_{oc}	K_d
Benzene	78.1	1270	0.0617	0.114	2.17	91.2	0.018
Toluene	92.1	361	0.017	0.124	2.69	302	0.060
Ethylbenzene	106.2	111	0.00603	0.135	3.2	977	0.195
O-xylene	106.2	135	0.00407	0.087	3.16	891	0.178
M-xylene	106.2	113	0.00468	0.125	3.3	1230	0.246
P -xylene	106.2	104	0.00427	0.130	3.27	1148	0.230
1,3,5-TMB	120.2	36.9	0.00148	0.207	3.42	1622	0.324
1,2,4-TMB	120.2	40.6	0.00112	0.143	3.65	2754	0.551
1,2,3-TMB	120.2	49.7	0.000933	0.097	3.6	2455	0.491
Naphthalene	128.2	51	0.00012	0.013	3.33	1318	0.264

Table 3.1 Note: Properties corrected to average groundwater temperature of 10 °C, where molar weight – MW; vapour pressure P_i; dimensionless Henry's Law air-water partition coefficient K_H; aqueous

solubility S_i^{sat}; octanol-water partition coefficient K_{ow}; organic carbon/water partition coefficient K_{oc},; and the soil –water distribution coefficient K_d obtained from Environmental Organic Chemistry 2nd Edition (2003) and (SPARC, 2009).

3.3 Contaminant Distribution

The source area consists of a complex distribution of free-phase and residual NAPL, aqueous and vapour phase contaminants which can partition into vadose zone and aquifer materials. Site investigation involved the occasional recovery of NAPL in select monitoring wells, the collection of soil cores to determine the presence of residual NAPL and groundwater quality sampling at discrete intervals using multilevel wells to evaluate the distribution of contaminants in the aquifer profile as part of the research project.

3.3.1 Seasonal Water Table Fluctuations

Free product has been recovered from monitoring wells MW-102 (screened 1.5 -9.2 m bgs), MW-1 (screened 4.6-7.6 m bgs), MW-301-6 (screened 5.8-6 m bgs), MW-401-1 (screened 5-5.5 m bgs) and MW-401-2 (screened 5.5 – 6 m bgs) throughout the duration of the Site investigation. NAPL distribution in the subsurface is influenced by the location of the water table, where the amount of free phase decreases at higher water levels Oliveira (2009). Residual NAPL can undergo re-mobilization in the subsurface related to a declining water table involving imbibition and drainage of the porous media, resulting in larger NAPL thicknesses being observed and recovered in monitoring wells. The observed NAPL thickness trend at the Site is consistent with Oliveira (2009), where greater NAPL thickness is present during periods of low groundwater levels in the fall months based on historical Site data provided by SNC Lavalin.

Seasonal variability of the water table, combined with the downgradient migration of the mobile NAPL has created a complex re-distribution of contaminants in the heterogeneous setting. LNAPL floating on the capillary fringe tends to migrate downwards with seasonal water table decline and may become trapped at greater depths by capillary forces or underneath low permeable units following periods of water table rise. Evidence of this occurring at the Site has been observed in multilevel well MW-301 port 6 screened between 305.6 and 305.4 m AMSL (5.8 and 6 m bgs) in sandy gravel materials where free product has been recovered at various times throughout the year up to 3 m below the then-current water table. The sandy gravel unit containing the NAPL pool is overlaid by approximately 0.75 m of lower permeability fine sand that likely prevented the re-mobilization of the NAPL during water table rise.

In an unconfined aquifer, LNAPLs can pool as a lens at the capillary fringe and move laterally in response to capillary and gravitational forces where ganglia occurring below the lens at lower saturation are trapped as small, isolated and discontinuous droplets (Chevalier et al, 1998). Seasonal water table level fluctuations result in a smear zone (Reddi & Pant, 1998) about 5 m thick at the Site between 309 and 304 m AMSL, which coincides with the vertical extent of the minimum (1.5 m bgs) and maximum (6.5 m bgs) water table fluctuations as previously discussed in Chapter 2. The distribution of residual NAPL contamination present within the study area was determined by using soil extraction techniques discussed in more detail in Section 3.3.2.

3.3.2 Residual Phase NAPL in the Select Research Area

The selected research area was determined from the compilation of historical soil and groundwater analysis provided by SNC Lavalin, in conjunction with soil core data obtained during the November 2007 and July 2009 installation of multilevel wells (see Figure 3.1). Borehole (BH) locations correspond to existing monitoring well (MW) locations. Soil cores were collected using a hollow stem split spoon auger. Soil cores were located in the expected area of residual LNAPL, based on previous SNC-Lavalin reports and proximity to the location of former USTs and loading racks. Soil cores were analyzed for critical aromatics BTEXTMB as described in Appendix B.

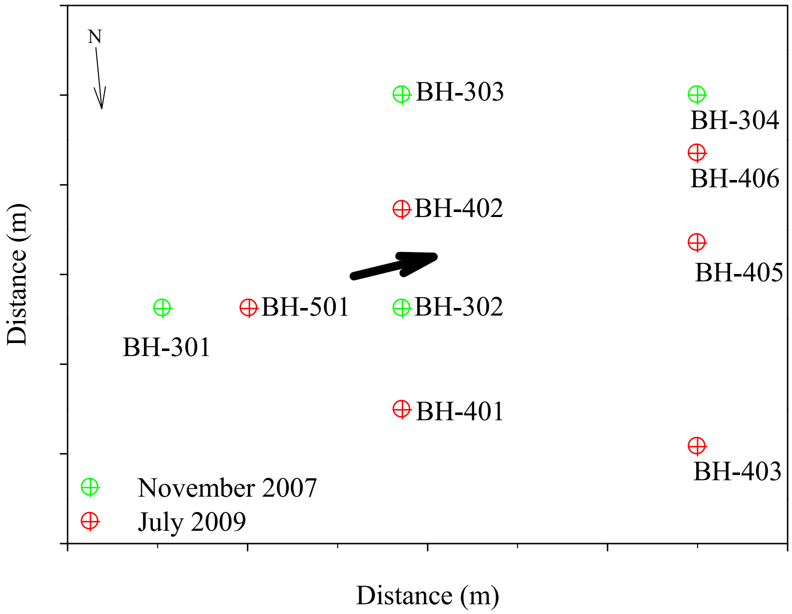

Figure 3.1: Plan view map showing location of borehole coring used to determine the vertical and spatial distribution of residuals in the research area. Multilevel monitoring wells were installed at each borehole location (e.g. BH-301 equivalent to MW-301), with the exception of BH-501, where a single monitoring/injection well was installed.

3.3 Estimation of the Mass of Residuals

Soil concentrations were used to infer the presence of LNAPL residuals using the method of Feenstra et al. (1991). This method considers the total chemical found in the soil to be distributed at equilibrium between the pore water of the sample, sorbed on the soil solids, and present in the soil gas (Feenstra et al., 1991). Initially, LNAPL phase is assumed not to be present. The maximum aqueous concentration of an aromatic is taken as the effective concentration of that chemical (S_i^e), given its mole fraction in the Site NAPL.

Considering the contaminants present in the subsurface originated from LUSTs, the composition of the NAPL released likely varied historically. However, for the purpose of the research project, NAPL is assumed to be consistent in composition throughout the entire study area. The maximum total soil concentration can then be computed, assuming equilibrium partitioning of the chemical between aqueous, vapour, and sorbed phases. If the actual measured soil concentration exceeds the computed maximum soil concentration, then additional chemical must be present in the soil in the form of NAPL. Thus, the approach identifies the presence of NAPL when the hypothetical maximum concentration of a chemical, C_t, exceeds the concentration measured in the soil. C_t is defined by equations (3.1) to (3.3):

$$C_t = \frac{M_s + M_w + M_a}{\rho_b} \tag{3.1}$$

$$C_t = \frac{C_s\rho_b + C_w\Phi_w + C_a\Phi_a}{\rho_b} \tag{3.2}$$

$$C_t = \frac{K_d C_w\rho_b + C_w\Phi_w + C_a H_c\Phi_a}{\rho_b} \tag{3.3}$$

Where:

M_s - mass of chemical sorbed on soil solids (mg);

M_w - mass of chemical in pore water (mg);

M_a - mass of chemical in soil gas (mg);

ρ_b - dry bulk density of the soil sample (g/cm^3);

C_{ti} - the total soil chemical concentration (mg/kg dry weight);

C_s - chemical concentration sorbed on the soil solids (mg/kg dry weight);

C_w - chemical concentration in the pore water (mg/L);

C_a - chemical concentration in the soil gas (mg/L);

φ_w - water-filled porosity (volume fraction);

φ_a - air-filled porosity (volume fraction);

K_d - partition coefficient between pore water and soil solids (cm^3/g);

H_c - dimensionless Henry's Law Constant;

i - gasoline constituent.

K_d, partition coefficient between the sediments and pore-water, is computed using equation (3.4):

$$\mathrm{K_d} = \mathrm{K_{oc}}\,\mathrm{f_{oc}} \tag{3.4}$$

Where K_{oc} is the organic carbon-water partition coefficient for the gasoline constituent and f_{oc} is the fraction of organic carbon in the soil. A conservative estimate of f_{oc} equal to 0.0002 was selected for this calculation based on f_{oc} data determined for the Borden sandy aquifer (Mackay et al., 1986a)

Re-arranging the equation in terms of the pore-water concentration yields equation (3.5):

$$C_w = \frac{C_t \rho_b}{K_d \rho_b + \phi_w + H_c \phi_a} \tag{3.5}$$

Equation (3.5) can be simplified to equation (3.6) by neglecting $H_c\Phi_a$, since the core was water-saturated:

$$C_w = \frac{C_t \rho_b}{K_d \rho_b + \phi_w} \tag{3.6}$$

The total soil concentration can then be expressed in terms of the pore-water concentration by equation (3.7):

$$C_t = \frac{K_d C_w \rho_b + C_w \phi_w}{\rho_b} \tag{3.7}$$

The effective solubility S_i^e of the chemical of interest *i* was used as the pore-water concentration C_w to determine the maximum total concentration within the pore-space in the absence of a NAPL phase as presented in equation (3.8) adapted from Raoult's Law:

$$S_i^e = X_{i_{NALP}} S_i^{sat} \tag{3.8}$$

Where $X_{i\,NAPL}$ is the mole fraction of the chemical constituent in the gasoline mixture and S_i^{sat} is the pure phase solubility of the compound (Shiu et al, 1998).

This relationship has been reasonably approximated by laboratory studies conducted by Banerjee (1984) for structurally similar hydrophobic organic liquids and an error not to exceed a factor of two for complex organic mixtures (Leinonen et al., 1973). The mole fraction of selected gasoline components in the weathered NAPL recovered on-Site (Appendix B Table B.1) was used in this analysis.

The total soil extract concentrations determined using equation (3.9) are expressed in mg/kg dry soil which were converted to wet soil concentrations and compared to concentrations of contaminants measured in the field cores by the following expressions (3.9 and 3.10):

$$\rho_m = \rho_b + \phi_w \rho_w \tag{3.9}$$

$$C_{t_i} = \frac{K_d C_w \rho_b + S_i^e \phi_w}{\rho_b} \times \frac{\rho_b}{\rho_m} \tag{3.10}$$

Where ρ_m is the wet bulk density of the soil, 2.13 g/cm^3 based on an average dry bulk density of 1.81

g/cm^{3}and measured effective porosity of 0.32 of field sediments determined following procedures described by Oldham (1998).

According to Feenstra et al. (1991), where C_{ti} exceeds the soil extract concentration for the individual gasoline compound, residuals are inferred to be present. It should be noted that an amount of uncertainty exists for the mole fraction of aromatics in the Site NAPL. It is also likely that the Site NAPL is not uniform, given the potential for multiple releases and differential weathering of the LNAPL in situ. Therefore, the sum of the calculated soil extract concentrations (C_{ti}'s) for BTEXTMB was used to infer the presence of residuals as opposed to the individual gasoline constituents. This should eliminate the identification of the presence of NAPL due to a single chemical exceedence. The calculated hypothetical maximum total soil concentration for BTEXTMB present in the source zone without there being NAPL present is 13 mg/kg wet soil (see Table 3.2). A summary of the total soil concentrations for individual gasoline constituents is presented in Table 3.2.

Table 3.2: Calculated hypothetical maximum total soil concentration for the gasoline constituents of interest *i*, including applicable parameter values.

Component	Log K_{ow}	K_{oc}	K_d	$X_{i\text{-NAPL}}$	S_i^{sat} (mg/L)	C_{ti} (mg/kg wet soil)
Benzene	2.13	83.2	0.017	0.027	1270	**6.08**
Toluene	2.65	275	0.055	0.008	361	**0.65**
Ethylbenzene	3.15	871	0.174	0.018	135	**0.64**
P,M-xylene	3.15	871	0.174	0.056	113	**2.01**
O-xylene	2.91	501	0.1	0.022	135	**0.74**
1,3,5-TMB	3.65	2750	0.551	0.015	48.2	**0.47**
1,2,4-TMB	3.65	2750	0.551	0.048	57	**1.77**
1,2,3-TMB	3.66	2820	0.564	0.011	49.7	**0.39**
Naphthalene	3.4	1550	0.31	0.004	51	**0.09**
Total						**13**

Log K_{oc} =log K_{ow} - 0.21 for PAHs (Karickhoff et al. 1979) , C_{ti} - hypothetical maximum total soil gasoline constituent concentration , X_{iNAPL} - mole fraction, S_i^{sat} - pure-phase solubility, S_i^e - effective solubility, K_{ow} and K_{oc} are dimensionless

Residuals are assumed to be present when the BTEXTMB soil concentration exceeds the Feenstra detection value, however due to the extremely high concentrations of contaminants measured; there is evidence to suggest contaminants may become mobilized based on their detection from sampling events conducted at periods of low and moderate water table elevations. Typical residual saturation of LNAPL volume to the volume of pore volume can range from 10-20% in the unsaturated zone to 15-50% of the pore volume in the saturated zone as described by Mercer & Cohen (1990).

Residual saturation provides an indication as to the concentration above which LNAPL may be mobile and below which LNAPL will be immobile due to entrapment by capillary forces. NAPL must displace water from the pore space within the capillary fringe and overcome the capillary pressure in order to migrate laterally. Wilson and Conrad (1984) established that NAPL could undergo both vertical and horizontal re-mobilization in gravel materials, whereas movement was restricted to vertical movement in sand and inhibited in clay and silt.

The NAPL concentration at 100% residual saturation ($C_{100\%\,Sr}$) present in the select research area was determined using equation (3.11) below:

$$C_{100\%\,Sr} = \frac{S_r n\, G_{NAPL}}{(1-n)G_{solids}} \tag{3.11}$$

Where:

S_r – residual saturation

n – porosity, 0.32

G_{NAPL} – specific gravity of aquifer materials, 0.80 g/cm^3

G_{solids} – specific gravity of aquifer materials, 2.7 g/cm^3

The application of equation (3.11) to site specific conditions yields a maximum concentration of NAPL of approximately 140,000 mg/kg. The NAPL continuum developed by Boynton (2009) states that NAPL has the potential to be mobilized or recovered at saturation exceeding 10%, equivalent to 14,000 mg/kg NAPL. BTEXTMB gasoline constituents comprised approximately 21% of the total NAPL recovered from the Site. Based on the measured composition of the NAPL, BTEXTMB soil extract concentrations exceeding 3,000 mg/kg (10% of 14,000 mg/kg TPH) would be the expected minimum concentration required for the NAPL to be mobile.

3.3.1 Coring Results

Characterization of the residual distribution in the study area was determined by soil coring activities that took place in November 2007 and July 2009. Coring was conducted within the former locations of UST and loading racks (BH-301 and BH-501), downgradient in Row 1 (BH-302, BH-303, BH-401, BH-402) and further downgradient within the source zone, Row 3 (BH-304, BH-403, BH-405 and BH-406), as presented in Figure 3.1.

Using the Feenstra et al. (1991), residuals are inferred to be present when the total soils extract concentrations of BTEXTMB exceed 13 mg/kg wet soil. The total soil concentrations measured in the majority of the samples are significantly greater than 13 mg/kg. The inference of residuals at BTEXTMB soil concentrations exceeding 13 mg/kg is in general agreement with the value exceeding 11 mg/kg where residual are inferred for Borden sand (Yang, 2008).

The vertical distribution of BTEXTMB is presented in Figures 3.2 to 3.4, in order of increasing distance downgradient from the presumed release area. Trends of total BTEXTMB concentrations in individual cores were highly variable throughout the vertical profile. BTEXTMB soil extract concentrations measured during the coring program were consistently greater than 13 m/kg, however less than 3,000 mg/kg which is an indication that NAPL is primarily present in the study area at residual saturation and possibly immobile. Results of the soil coring investigation are summarized in Table B.2 through B.11 in Appendix B.

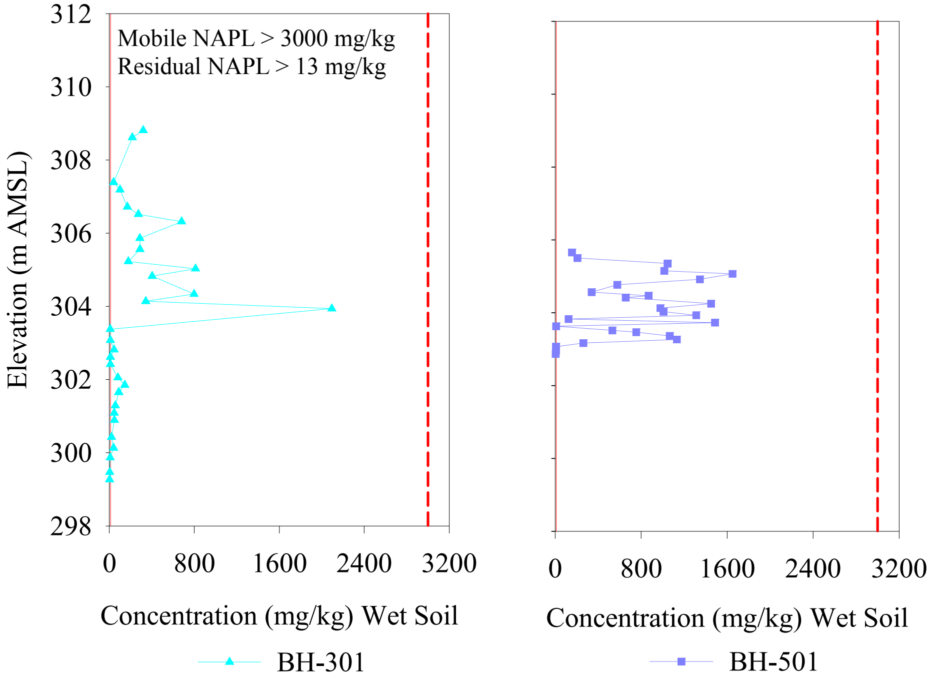

Figure 3.2: Soil concentrations of BTEXTMB in soil cores BH-301 (MW-301) and BH-501 (MW-501, injection well). Residuals inferred at BTEXTMB concentrations exceeding 13 mg/kg wet soil (red line). Mobile NAPL inferred at BTEXTMB concentrations greater than 3,000 mg/kg wet soil.

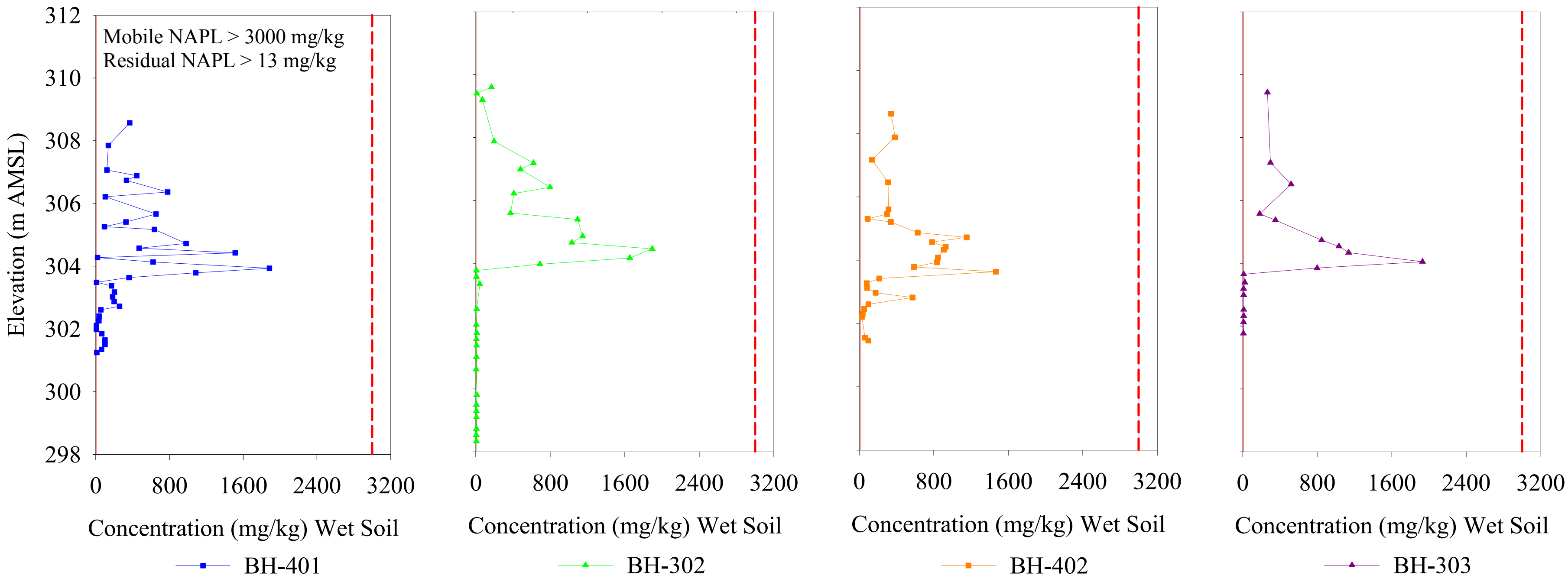

Figure 3.3: Vertical distribution of contaminants in cores of Row 1, north-south transects across the study area (left to right); BH-401 and BH-402 recovered July 2009 (groundwater elevation 307.25 m AMSL). BH-302 and BH-303 coring took place November 2007 (groundwater elevation 304.11 m AMSL). Correlation between the peak concentrations in each of the cores occurs at approximately 304 m AMSL.

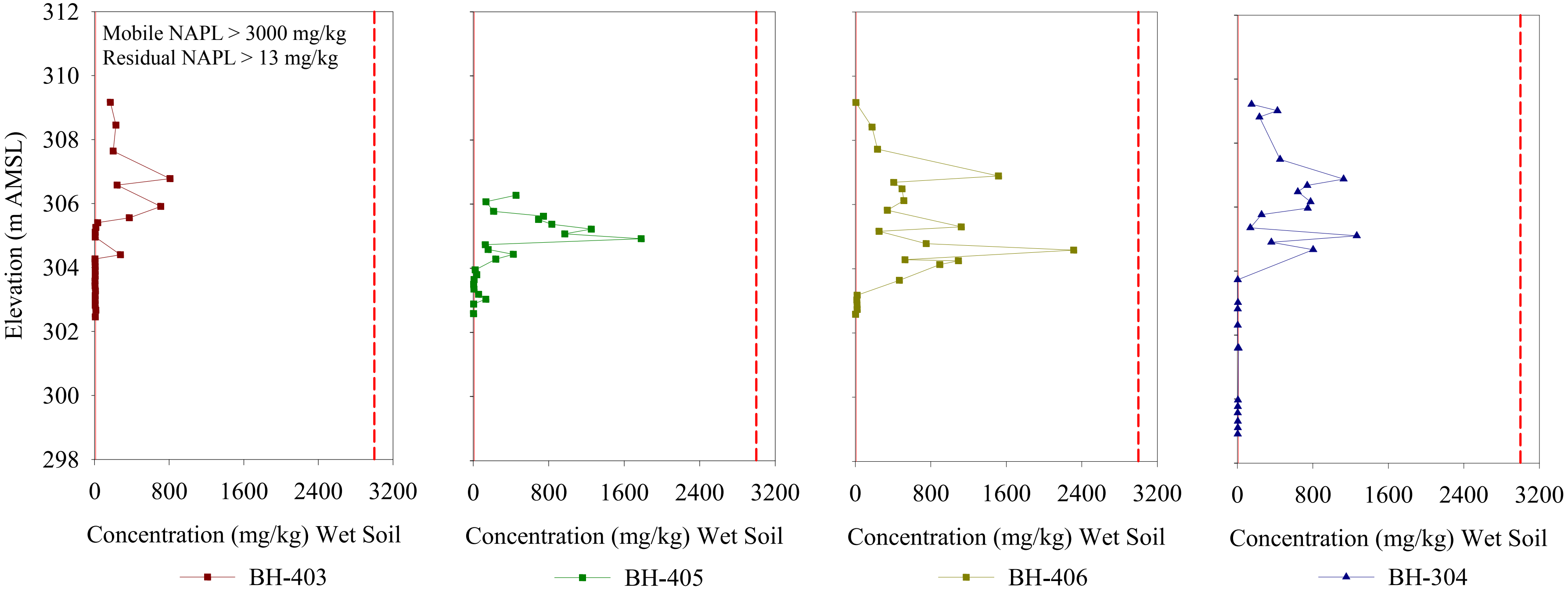

Figure 3.4: Vertical distribution of total BTEXTMB in cores of Row 3 recovered July 2009 (groundwater elevation 307.25 m AMSL). BH-304 coring took place November 2007 (groundwater elevation 304.11 m AMSL).

LNAPL has the ability to migrate below the water table and become trapped at lower elevations due to seasonal fluctuations in addition to LNAPL being confined to the network of larger pore-spaces. The distribution of contaminants observed at the Site is generally not consistent with the standard conceptual model where the bulk of the NAPL is present above capillary fringe as discussed in Section 3.1. The results of the coring investigation at the Site reveal the bulk of the NAPL distribution to be found below the water table.

The maximum concentration of total critical aromatics in soil were generally concentrated around 305 m AMSL during fall 2007 and July 2009 and independent of the location of the water table at the time of coring, about 304.1 m AMSL and 307.3 m AMSL, respectively. The elevated concentration of contaminants in the soil at this level may be attributed to the presence of potential mobile NAPL even though concentrations less than 3,000 kg/mg wet soil were observed.

The residual hydrocarbon distribution in the unsaturated and saturated zone is consistent with the seasonal minimum and maximum groundwater elevations, where a smear zone has been generated by the fluctuating water table. The concentration of residual NAPL decreases significantly beyond the minimum seasonal groundwater low where no residual contamination is inferred beyond elevation 308.9 m ASML (11.5 m bgs) for BH-301, 311.5 (8.6 m bgs) for BH-302, 312.2 (7.9 m bgs) BH-303 and 313.7 (7.2 m bgs) for BH-304.

3.3.3 Dissolved Phase within the Source Zone

Four multilevel wells were installed by the University of Waterloo in November 2007 as part of the preliminary research to determine the vertical distribution of the contaminants in the dissolved phase in the locations corresponding to boreholes BH-301, BH-302, BH-303 and BH-304. The groundwater flow system serves as the primary migratory pathway for petroleum hydrocarbon impacted groundwater. The results of the groundwater sampling program were used to determine whether concentrations of contaminants of interest in the dissolved phase were consistent with the presence of residual LNAPL. A summary of the well details was previously discussed in Chapter 2 with additional relevant well information presented in Appendix A.

Groundwater samples were collected from the 300 Series UW multilevel wells and analyzed for total BTEXTMB on four occasions corresponding with seasonal groundwater maxima and minima: December 2007, May 2008, November 2008 and April 2009 (Figure 3.5). BTEXTMB concentrations in the dissolved phase of the source zone ranged between 900 µg/L and 42,000 µg/L. The highest concentration was measured in MW-301, located at the eastern portion of the source zone, closest to the former LUSTs (see Figure 3.1). Maximum dissolved phase concentrations generally decreased downgradient within the source zone from MW-302 and MW-303 (Row 1) to MW-304 (Row 3) situated approximately 6 m away. On all sampling occasions, concentrations generally increased with depth, with peak concentrations occurring between 305 and 303 m AMSL located within the proximity of seasonal groundwater minimum at the Site.

Only slight differences in the vertical distribution of contaminants in the groundwater were noted between periods of low water table elevation (fall) and high water table (spring), however a similar contaminant profile is apparent under the different hydrogeologic conditions. The variability in measured concentration of BTEXTMB within the 4 seasonal sampling events may be attributed to transient nature of the aquifer, where groundwater elevation, flow path and changes in the contact zone of NAPL dissolution of the saturated zone influence the aqueous concentrations (Davis et al., 1999). Complete results of the four groundwater sampling events are presented in Appendix B, Table B.13 through B.17.

The history of the release of LNAPL is unknown, however the source zone has likely been established from several spill events, as a single release event is not documented resulting in several LNAPL compositions being present. The percentage of aromatics in gasoline can vary considerably depending on the composition of the gasoline source (Cline et al., 1991), resulting in different estimates for the aqueous concentration S_i^e in equilibrium for a particular NAPL. A degree of uncertainty is

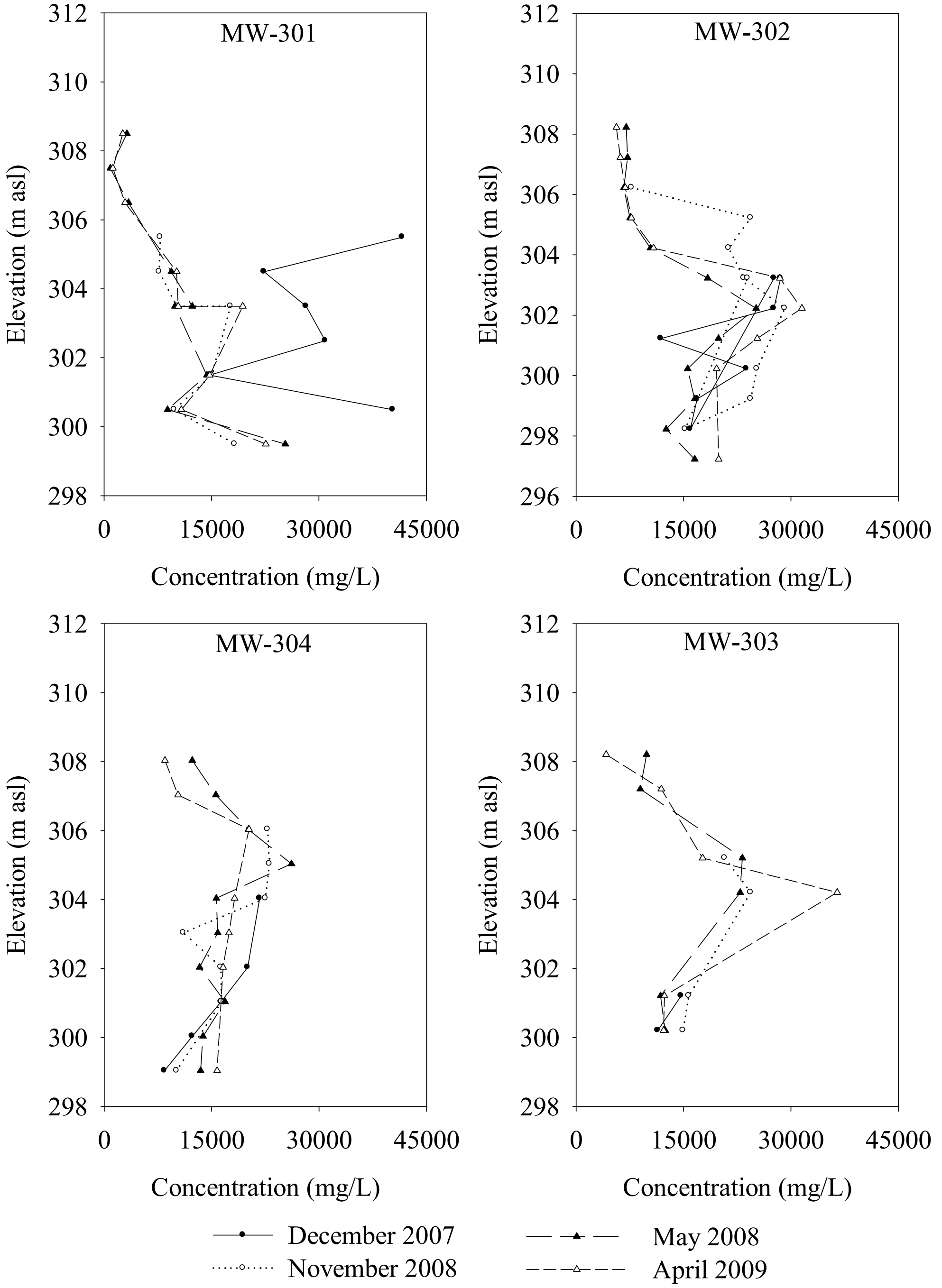

Figure 3.5: Vertical profile of the total groundwater concentrations BTEXTMB from November 2007 to April 2009 prior to remediation activities. MW-301 is situated at the top of the source zone, MW-302 and MW-303 are located in Row 1, further downgradient of MW-301 and MW-304 is situated in Row 3, furthest downgradient within the source zone.

associated with the application of Raoult's Law in this case considering the amount of variability associated in the LNAPL and the variation in the rate of dissolution over time. As a result, the LNAPL present at the Site in April 2008 may be even more variable due to weathering. The analysis of Site LNAPL is presented in Appendix B Table B.1 as previously discussed in section 3.3.

The existence of NAPL was also inferred using an adaptation of Raoult's Law, where the aqueous concentration S_i^e in equilibrium with the NAPL, or effective solubility was calculated (see equation 3.8). A summary of approximate aqueous concentrations of gasoline constituents in equilibrium with NAPL is presented in Table 3.2, based on mole fractions determined from analysis of NAPL recovered from well MW-102 at the Site on one occasion in April 2008 (Table B.1). To illustrate the calculation, aqueous concentrations measured in multilevel well MW-301-8 are compared to the calculated equilibrium aqueous concentrations determined using Raoult's Law in Table 3.4.

Table 3.4: Presence of NAPL inferred using Raoult's Law by comparing observed groundwater concentrations with LNAPL collected from the Site.

Component	S_i^e (mg/L)	C_i (mg/L)	NAPL Inferred
Benzene	35.9	1.5	NO
Toluene	3.2	19.4	YES
Ethylbenzene	2.1	2.7	YES
P,M-xylene	6.6	9.7	YES
O-xylene	3.1	4.0	YES
1,3,5-TMB	0.8	0.6	NO
1,2,4-TMB	2.8	2.5	NO
1,2,3-TMB	0.6	0.7	YES
Naphthalene	0.2	0.5	YES

Groundwater concentrations of toluene, ethylbenzene, xylenes, 1,2,3-TMB and naphthalene recovered from the multilevel wells MW-301, MW-302, MW-303 and MW-304 are comparable to concentrations in equilibrium with the NAPL. However, concentrations of benzene, 1,3,5-TMB and 1,2,4-TMB measured in the groundwater are less than the expected concentrations to infer the presence of NAPL based on the December 2007 sampling event. Yang (2008) reported that mass transfer from

NAPL may not always occur according to Raoult's Law which is consistent with the notion that NAPL dissolution process at larger scales has been found to be mass transfer limited (Chatzis et al., 1983; Salhand et al., 2002).

The results of the groundwater sampling program were used to determine whether concentrations of contaminants of interest in the dissolved phase were consistent with the presence of residual LNAPL. Measured concentrations of gasoline constituents of interest required to infer the presence of residual NAPL in the subsurface were determined using the Feenstra et al. (1991) and Raoult's Law, while comparing the results of groundwater sampling and soil coring activities. The vertical distribution of select gasoline constituents, benzene and toluene present in the dissolved and soil phase is illustrated in Figure 3.6. The presence of residual NAPL was inferred when BTEXTMB total soil concentrations exceeded 13 mg/kg (wet soil) or more specifically 0.65 and 6.08 mg/kg (wet soil) for concentrations of individual gasoline constituents toluene and benzene, respectively.

The results of the two methods for inferring the presence of NAPL are variable depending on the chemical of interest as seen in Figure 3.6, where toluene (Fig. 3.6b) present in NAPL is generally consistent with the two methods compared to benzene (Fig 3.6a). The measured concentrations of benzene in MW-301-8 are significantly lower than the expected aqueous solubility of 35.9 mg/L, however residual benzene was inferred using Feenstra et al. (1991). The discrepancies between the two methods is likely attributed to the mass transfer limited dissolution of NAPL as previously discussed.

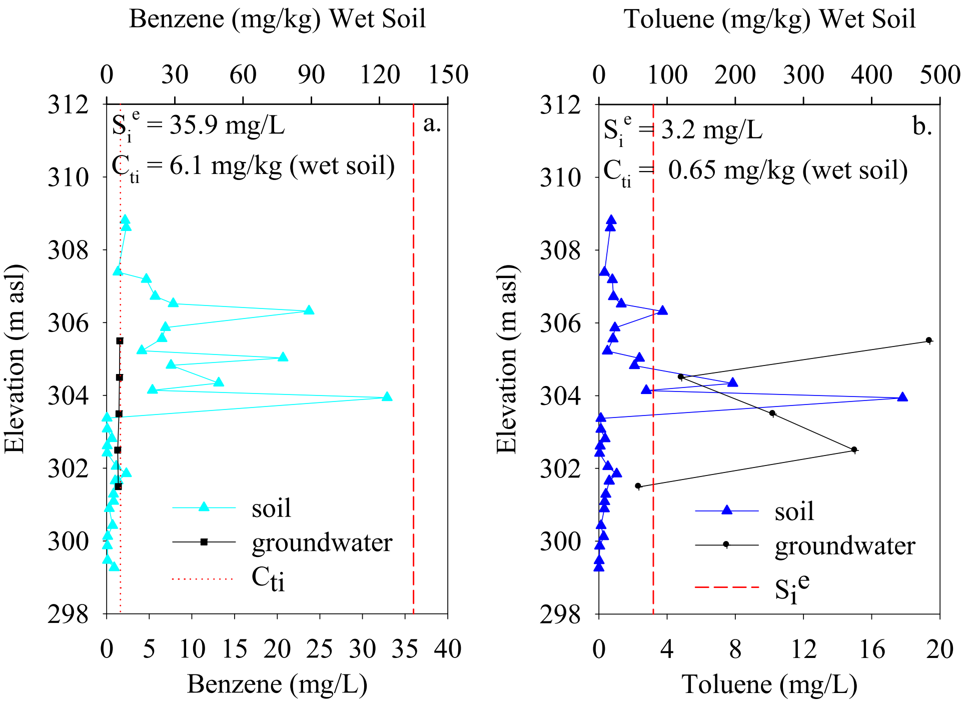

Figure 3.6: Comparison between the inference of NAPL based on concentrations of benzene (a) and toluene (b) measured during soil coring and groundwater sampling using the Feenstra et al. (1991) method and Raoult's Law.

3.3.4 Residual Distribution and Hydraulic Conductivity

The distribution of NAPL residuals in the subsurface is influenced by 3 factors: (1) location and extent of the original spill(s) (2) heterogeneity of the porous medium and (3) seasonal variability in the water table elevation (Sharma & Mohamed, 2003). The source zone is generally located within the vicinity of the former UST and loading racks, however the extent and history of the spill(s) is unknown at the Site.

The results of the vertical hydraulic conductivity and petroleum hydrocarbon distribution profiles were compared to one another in order to determine whether a correlation exists as illustrated in Figure 3.7 for boreholes BH-501, BH-401, BH-402, BH-403, BH-405 and BH-406. There does not appear to be a direct correlation between hydraulic conductivity of the porous media and the residual concentration in the cores (Figure. 3.7). Peak concentrations of BTEXTMB were measured in both high and low conductive materials. The concentrations of petroleum hydrocarbons are quite variable throughout the vertical profile, where both lower ($K = 10^{-7}$ m/s) and had higher conductive materials ($K = 10^{-4}$ m/s) had BTEXTMB soil concentrations below the residual limit of 13 mg/kg wet soil to greater than 1,500 mg/kg wet soil. The poor correlation between the distribution of residual NAPL and hydraulic conductivity indicates that additional factors are contributing to the extent of the source zone that are presently not fully understood. The variability of hydraulic conductivity with elevation is illustrated in Figure 3.8.

The low BTEXTMB concentration measured at the bottom of the coring extent may be related to the lower hydraulic conductivity (Fig. 3.8), however it more likely reflects the lack of water table smearing of contaminants and capillary forces that trapped the NAPL at higher elevations, but not at such low elevations (Figure 3.9). The higher permeability sand and gravel layer, Unit 3 situated approximately between 306.5 and 305.3 m AMSL is able to transmit NAPL more effectively than the lower K zones of Unit 4 and Unit 5.

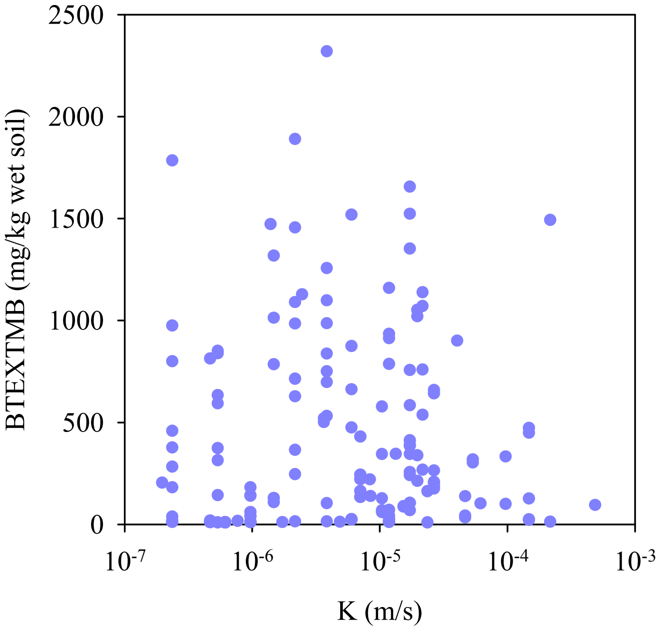

Figure 3.7: Poor correlation between horizontal hydraulic conductivity, K (m/s) and BTEXTMB soil concentrations (mg/kg wet soil) in boreholes BH-501, BH-401, BH-402, BH-403, BH-405 and BH-406

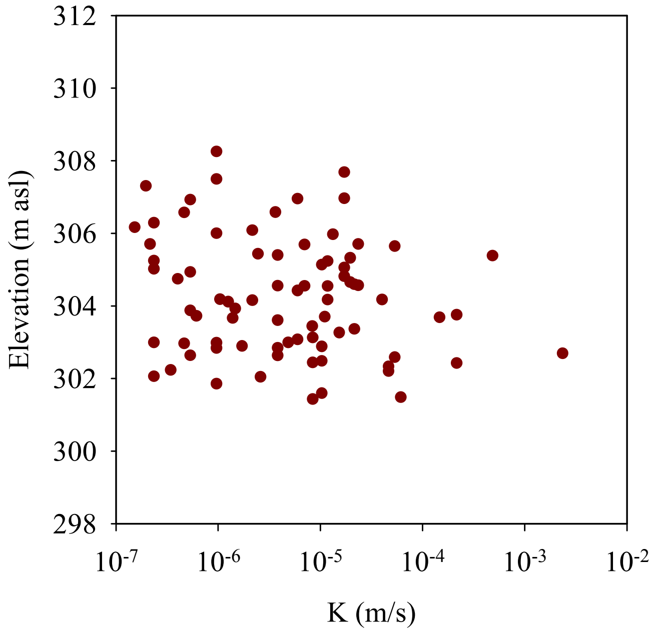

Figure 3.8: Correlation between horizontal hydraulic conductivity, and depth in boreholes BH-501, BH-401, BH-402, BH-403, BH-405 and BH-406.

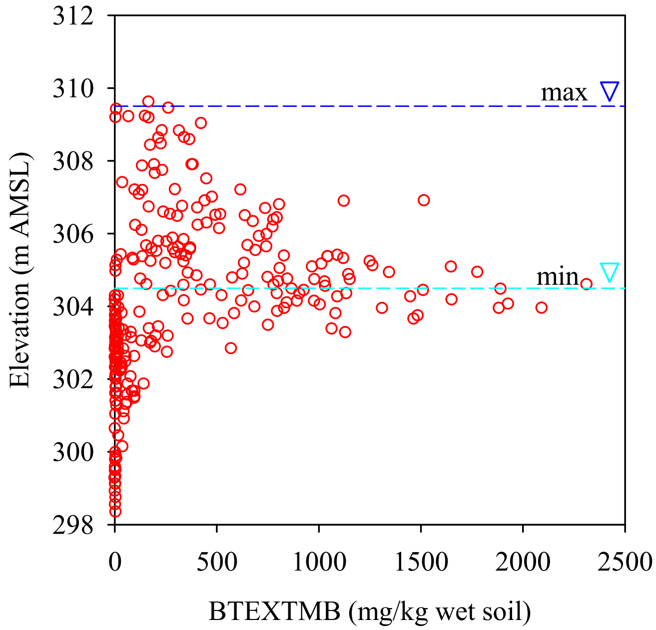

Figure 3.9: Correlation between horizontal ground elevation and BTEXTMB soil concentrations (mg/kg wet soil) in boreholes BH-501, BH-401, BH-402, BH-403, BH-405 and BH-406, including the average maximum and minimum water levels observed at the Site.

Chapter 4: Laboratory Microcosm Experiment

4.1 Introduction

The objective of the experiment was to demonstrate the consumption of aromatics in a controlled anaerobic setting, utilizing nitrate as a terminal electron acceptor in order to confirm the suitability of the remediation technology at the field setting. Groundwater was collected from on-site petroleum impacted monitoring wells (MW-501 and MW-302 Port 7) situated within the remedial zone of interest and amended with nitrate and necessary nutrients to enhance microbial degradation of gasoline constituents through denitrification in a laboratory controlled microcosm experiment. Microcosm experiments can be used to demonstrate that a particular compound can and does degrade under ambient subsurface conditions and in the evaluation of the effect of environmental variables on the rate and extent of biodegradation (Border et al., 1997).

4.2 Acetylene Block Technique Method

The microcosm experiment involved the anaerobic incubation of triplicate treatment test units consisting of a control, microbial active and microbial active amended with acetylene (C_2H_2). The acetylene (C_2H_2) block technique is used to inhibit the reduction of nitrous oxide (N_2O), to dinitrogen (N_2), resulting in an accumulation of N_2O, which is indicative of denitrification (Tiedje, 1982; Yoshinari & Knowles, 1976; Balderston et al., 1976)). The procedure involves the addition of purified acetylene gas to microcosms containing active microbial populations. Acetylene inhibits the function of nitrous oxide reductase, essentially stopping the reduction of nitrous oxide to elemental nitrogen (N_2), in which the rate of nitrous oxide accumulation can be measure.

BTEXTMB, F1-F3 fractions and TPH were measured in sacrificial microcosm test units throughout the course of the 63 day incubation period in order to assess the biodegradation of contaminants. Nitrate nitrite and nitrous oxide (acetylene amended treatment only) and DO were measured in sacrificial replicate microcosms throughout the duration of the incubation period which can be used order to establish the denitrification potential attributed to the consumption of petroleum hydrocarbons and evaluate the anoxic conditions.

Laboratory microcosms containing groundwater and aquifer sediments (dried) collected from the Site were augmented with nitrate and nutrients in 3 test treatments: 1) Sterile Control, 2) Active and 3) Active C_2H_2 amended with 1% purified acetylene gas. Acetylene gas was purified in a gas scrubbing train utilizing an acetylene trap scheme developed by Hyman & Arp (1987) to remove contaminants such as acetone and carbon monoxide (CO) which may interfere with denitrification. Each individual microcosm was spiked with a solution containing approximately 265 mg/L NO_3^- (0.24 mmol or 14.6 mg NO_3^-), serving as the primary electron acceptor under anaerobic conditions attributed to the dominant supply available. The acetylene block technique is useful for determining measurements of denitrification potential, especially in systems with high concentrations of nitrate (Groffman et al., 2006).

The test solution comprised of petroleum impacted groundwater mixed with nutrients and NO_3^- prior to being separated into two individual batches, Active (A) and Control (B) treatments. Batch A was prepared as described below for the Active and Active C_2H_2 treatments, while batch B (control) was also amended with 10% v/v sodium azide (NaN_3), which served as a biostat limiting microbial degradation by inhibiting NO_3^- reductase (Castignetti & Hollocher, 1982). Control treatment test vials and aquifer materials were also sterilized by autoclave prior to the dispensation of the test solution. Both batches were mixed for 1-hr using a magnetic stirrer prior to being dispensed into the designated vials.

Test treatments were prepared in sacrificial quadruplets, where 1 replicate per treatment was used to monitor DO levels per sampling occasion. Each microcosm unit was comprised of a 60 mL clear glass vial containing 15 g (dry weight) of pristine aquifer material, 55 mL of groundwater consisting 22 mg/L total petroleum hydrocarbons (TPH), spiked with 60 mg/L NO_3-N (265 mg/L NO_3^- in the form of sodium nitrate, $NaNO_3$) as the terminal electron acceptor and inorganic nutrients 5 mg/L NH_4-N as NH_4Cl and 2 mg/L phosphorus as KH_2PO_4 leaving approximately 4 mL of headspace. Control and active test units were sealed with a Teflon-lined septum screw cap, while the Active C_2H_2 units were sealed with a Minivert^{TM} valve screw cap in order to facilitate the addition of purified acetylene gas. The Mininert ^{TM} cap was quickly removed and approximately 1 mL of purified C_2H_2 was added to each Active C_2H_2 vial via syringe followed by recapping and manually shaking the vial for 30 seconds in order for the aqueous phase to equilibrate with the 4 mL headspace.

Microcosms were prepared in the anaerobic chamber containing 1% CO_2, 2.5% H_2O and 96.5% N_2 gas, however batch test solutions were not mixed in the anaerobic setting considering the measured DO content of the test solution was below 1 mg/L and no headspace was present in the container during sample collection. The samples were subject to slight aeration (DO levels increased to approximately ~2 mg/L) as a result of the homogenization of the test solution, whereby the initial conditions of the microcosm test consisted of a mixed nitrate/oxygen setup. Batch solutions were mixed intermittently between dispensing test volumes, which re-suspended sediments and promoted representative samples between the treatments and test replicates. Table 4.1 summarizes the list of materials and amendments in each respective test treatment.

Table 4.1: Summary of microcosm test design applied in the study.

Batch	Treatment	Additives	Microcosm Setup
A	Active	NO_3^-, Nutrients	4 replicates containing 15 g (dry wt) pristine aquifer material, 55 mL test solution and 4 mL headspace in 60 mL vial, screw cap sealed
A	Active C_2H_2	NO_3^-, Nutrients, C_2H_2	
B	Control	NO_3^-, Nutrients, NaN_3 biostat	

The bulk of the test solution used for the microcosm study consisted of contaminated groundwater containing approximately 13 mg/L BTEXTMB and a total of 22 mg/L TPH. The amount of available organic contaminants serving as electron donors for microbial degradation was corrected to account for volatile contaminant mass that was removed from the aqueous phase through partitioning into the 4 mL of headspace. Approximately 15-30% reductions in TPH groundwater concentrations were observed in the sterile Control units between initial (day 0) and final measurements at the end of the experiment (day 63).

As the organisms present in the microcosm consume the contaminants, there's also a possibility that the volatile organic compounds could partition back aqueous phase and re-establish equilibrium. Henry's Law was applied in order to correct the initial dissolved contaminant concentrations and subsequent mass of organics available to the microbes for stoichiometric purposes as described in Appendix C. A summary of the corrected initial concentrations of the gasoline constituents of interest are presented in Table 4.2.

Table 4.2: Summary of initial organic contaminant content present in each microcosm as aqueous concentration, $C_{w,i}$; dissolved mass, M_i and number of moles , n_i of each constituent present.

Gasoline Constituent, i	$C_{w,i}$ (mg/L)	M_i (mg)	n_i (μmol)
Benzene	0.11	0.01	0.08
Toluene	1.0	0.06	0.61
Ethylbenzene	1.1	0.06	0.54
M,P-Xylene	4.2	0.23	2.18
O-Xylene	1.1	0.06	0.59
1,3,5-TMB	0.37	0.02	0.
1,2,4-TMB	1.6	0.09	0.71
1,2,3-TMB	0.49	0.03	0.22
Naphthalene	0.31	0.02	0.13
Total BTEXTMB	**10**	**0.57**	**0.53**
F1 Fraction	14	0.75	-
F2 Fraction	3.4	0.19	-
F3 Fraction	0.05	0.003	-
TPH	**17**	**0.94**	**-**

Sacrificial microcosm water was analyzed for organic contaminants: BTEXTMB, F1-F3 fractions, and Total Petroleum Hydrocarbons (TPH) in conjunction with NO_3^-, intermediate products NO_2^- and N_2O (Active C_2H_2 only) for evidence of denitrification. Organic contaminants of interest were analyzed by gas chromatography (GC) using a Hewlett Packard 5890 CG. Inorganic anions NO_3^- and NO_2^- were analyzed by a Dionex ICS 3000 equipped with a Dionex IonPac AS18 analytical column. Select samples were also analyzed for NO_3^- using the HACH® 2800 Portable Spectrophotometer Cadmium Reduction Method 8039 and NO_2^- using Diazotization, Method 8507. A comparison of the results of the two NO_3^- analysis methods are in good agreement, however positive interferences were inferred by ion chromatograph analysis for NO_2^-. Aqueous nitrous oxide N_2O samples were collected from Active C_2H_2 Treatments and analyzed using a Varian CP-3800 gas chromatograph with an ECD detector using the exetainer method. A summary of the sampling and analytical procedures is presented in Appendix C.

DO was measured using the HACH HQ40d DO probe (LBOD101), by gently passing the sample through a syringe connected directly to the probe sleeve in order to minimize intrusion of atmospheric O_2. Throughout the microcosm experiment, DO measurements were taken from 1 sacrificial replicate per treatment per sampling event. Due to limited sample volume, the O_2 was only measured in one test replicate per sampling event and assumed to be representative of the remainder vials. DO measurements were to confirm limited O_2 availability during the incubation period, where nitrate would be preferred as an electron acceptor in the oxidation of organic contaminants.

The total incubation period was 63 days, with sampling taking place on days 1, 3, 7, 10, 14, 28, 35 and 63. Sampling frequency, in part, was determined from the results of previous sampling events measuring the amount of BTEXTMB present in individual microcosm units. Evidence of denitrification driven by contaminant loss was inferred by declining NO_3^- concentrations corresponding to BTEXTMB concentrations in addition to the accumulation of intermediate products NO_2^- (Active + Active C_2H_2 treatments) and N_2O (Active C_2H_2 only) in the aqueous phase. The denitrification rate estimation was base on the acetylene block technique, quantifying the change in N_2O concentration over time (Sorenson, 1978; Knowles, 1990).

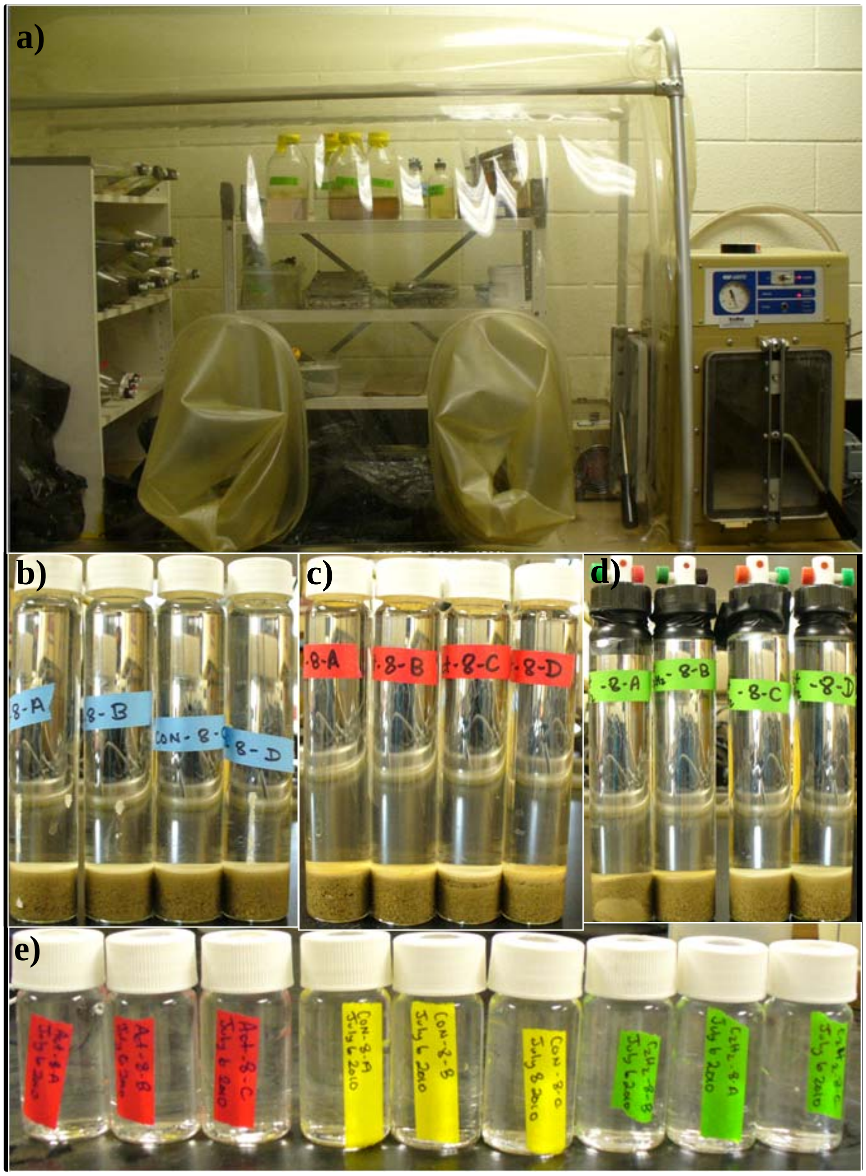

Figure 4.1: Microcosm Test Setup: a) Microcosms were incubated up to 63 days in the dark at room temperature (~20^{o}C) in the anaerobic glovebox; b) Control; c) Active; d) Active C_2H_2 (after an incubation period of 63 days) and e) 25 mL triplicate samples analyzed for BTEXTMB, F1-F3 Fractions and TPH.

4.3 Microcosm Results

4.3.1 Availability of Dissolved Oxygen

The initial (day 0) DO measurements of 2.4 mg/L in Batch A (Control) and 2 mg/L in Batch B were recorded and generally consisted of microaerophilic conditions. Dissolved oxygen in the Active and Active C_2H_2 amended microcosms declined to anaerobic conditions (DO < 2 mg/L) after 3 days of incubation as the test solution was temporarily exposed to atmospheric O_2 during preparation as previously discussed. Monitoring of DO levels in the Control treatment units were stable (approximately 2-3 mg/L) throughout the incubation period. Monitoring results of DO in the Control, Active and Active C_2H_2 treatments are presented in Figure 4.2. The approximate uncertainty associated with the DO measurements is about 0.5 mg/L and most often a positive bias.

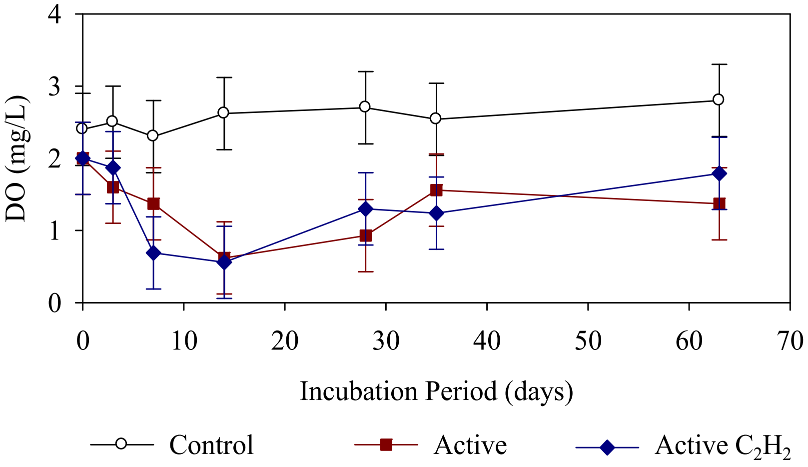

Figure 4.2: Monitoring results of DO measurements recorded from Control, Active and Active C_2H_2 microcosm treatments per sampling event with error bars (±0.5 mg/L

4.3.2 Biodegradation of BTEXTMB

Concentrations of gasoline constituents of interest benzene, toluene, ethylbenzene, xylenes, 1,3,5 trimethylbenzene (TMB), 1,2,4-TMB, 1,2,3-TMB and naphthalene, referred to as BTEXTMB were measured within each sacrificial treatment replicate at various times throughout the microcosm experiment in order to assess whether the native microbes are capable of degrading hydrocarbons under denitrifying conditions. A summary of the average normalized concentration changes over the 63 day incubation period in BTEXTMB aromatic hydrocarbons for the Control, Active and Active C_2H_2 treatments for the individual compounds is presented in Figure 4.3. A complete summary of the aqueous concentrations of individual aromatic compounds, petroleum hydrocarbon fractions and TPH is presented in Appendix C.

Average measured concentrations of BTEXTMB in the Control treatments (Fig. 4.3a) remained relatively unchanged throughout the duration of the experiment, which is consistent with the notion that sodium azide was applied to inhibit microbial activity. Declining concentrations of BTEXTMB were observed in the Active and Active C_2H_2 treatments attributed to biodegradation (Fig.4.3b,c) The removal of the mass of contaminants in the aqueous phase followed a sequential degradation pattern where ethylbenzene was the first compound to be fully removed followed by toluene and naphthalene (Figures 4.3b,c). The degradation of benzene appeared to be following a similar trend (up to 14 days) when conditions were likely microaerophilic. Degradation of o-xylene and the trimethylbenzene isomers underwent similar behaviour to benzene, however they did not exhibit big differences during the early phase of incubation time.

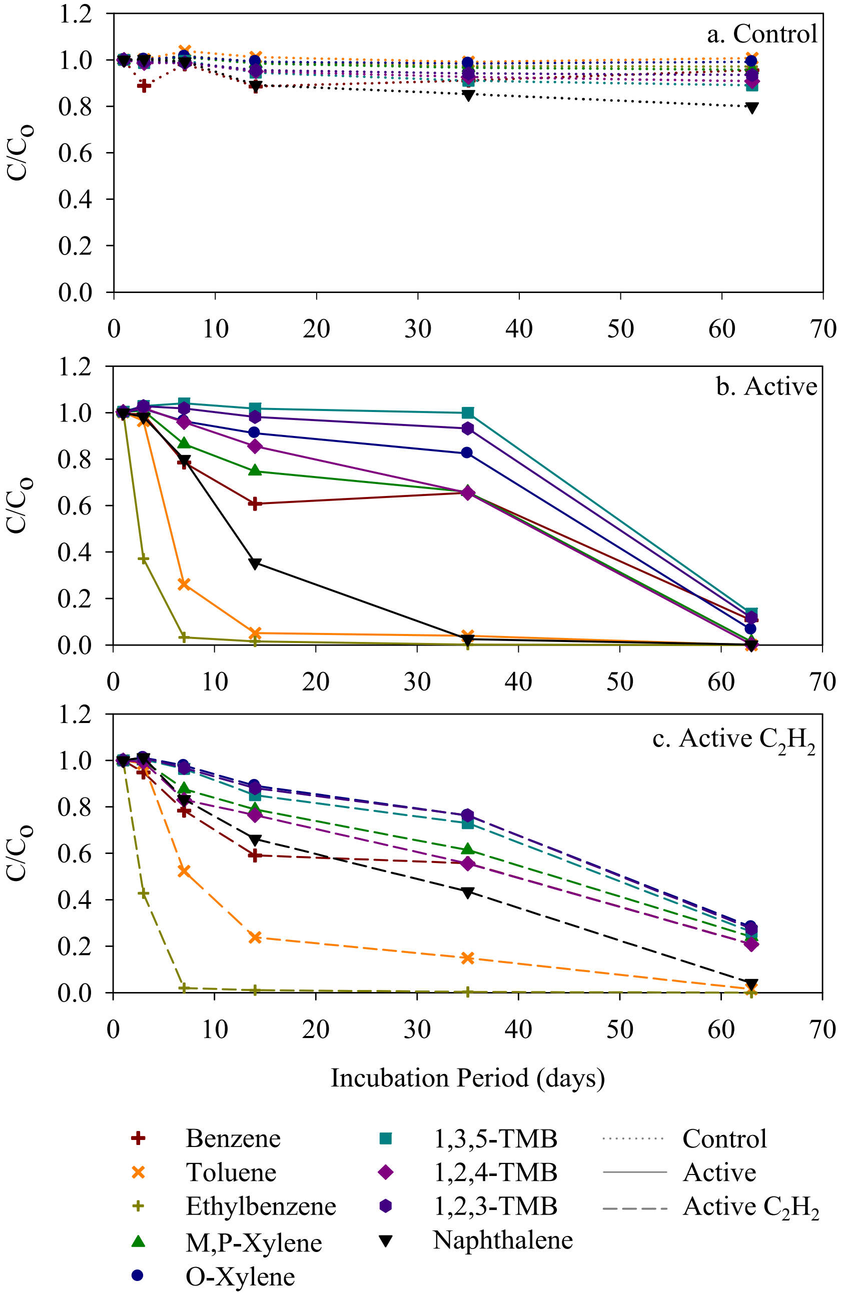

Figure 4.3: Normalized average gasoline constituent concentrations over time for Control (a), Active (b) and Active C_2H_2 (c) amended microcosms demonstrating sequential degradation of contaminants.

The relative concentration of a particular gasoline constituent, remaining on each sampling day, was determined by dividing the Active and Active C_2H_2 concentrations by that of the control treatment for that day, as follows:

$$\% \text{ remaining} = \frac{(C/C_o)_{\text{Active}}}{(C/C_o)_{\text{Control}}} \times 100 \quad (4.1)$$

Biodegradation of aromatic hydrocarbons is apparent in both treatments, however, a greater amount of contaminants were consistently removed in absence of the acetylene amendment. The percent remaining of aromatic hydrocarbons present in the active nitrate amended treatments is presented in below in Table 4.3.

Table 4.3: Summary of the average percent remaining of select aromatic hydrocarbons following 63 days of incubation under mixed microaerophilic and anaerobic conditions in nitrate amended microcosms relative to sterile controls.

Gasoline Constituent	% Remaining (s.d.) Active Microcosm	% Remaining (s.d.) Active C_2H_2 Microcosm
Benzene	9 (16)	21 (33)
Toluene	0 (0)	1 (3)
Ethylbenzene	0 (0)	0 (0)
M,P-Xylene	2 (3)	26 (42)
O-Xylene	8 (13)	29 (49)
1,3,5-Trimethylbenzene	16 (24)	30 (46)
1,2,4-Trimethylbenzene	0 (0)	24 (36)
1,2,3-Trimethylbenzene	14 (19)	30 (48)
Naphthalene	0 (0)	5 (7)
F1 (nC_6-nC_{10})	4 (6)	21 (34)
F2 (nC_{10}-nC_{16})	8 (9)	25 (32)
F3 (nC_{16}-nC_{34})	5 (2)	100 (67)
TPH (F1-F3)	5 (7)	22 (33)

The measured removal of contaminant mass present in the aqueous phase in each test unit is attributed to biodegradation, where the organisms utilized available terminal electron acceptors present in the test solution (limited O_2, NO_3^-) in the oxidation of organic contaminants to promote metabolic activities and population growth.

4.3.3 Denitrification

BTEXTMB reduction occurred concurrently with NO_3^- removal in the Active and Active C_2H_2 microcosm treatments. Denitrification in the microbial active microcosm test treatments was assessed by measuring concentrations of NO_3^- and intermediate products NO_2^- and N_2O (Active C_2H_2 only) at various times throughout the 63-day incubation period. Denitrification involves NO_3^- being reduced in the consumption of organic contaminants serving as the electron donor, whereby decreasing NO_3^- concentrations are accompanied by increasing concentrations of NO_2^- and N_2O. Measured concentrations of NO_3^- and denitrification intermediate products for the Active and Active C_2H_2 treatments are presented in Figures 4.4 and 4.5, respectively. Nitrate utilization and production of intermediates throughout the "replicate" microcosms was quite variable throughout the course of incubation period in both treatments as each replicate essentially acts as a unique microcosm.

Production of N_2O was observed and quantified in the Active C_2H_2 treatments (Fig. 4.5b). N_2O accumulation in the Active C_2H_2 treatment appears to cease after about day 35. The apparently stable N_2O concentrations 35 days of incubation may be attributed to the organic contaminants becoming limited as a result of biodegradation (see Figure 4.3). N_2O accumulates stoichiometrically from the reduction of NO_3^- and NO_2^- in a molar ration of 1:1, where 1 mole of NO_3^- or NO_2^- are consumed for every mole of N_2O produced as described in the reduced equations (4.2a) through (4.2f) below:

$$NO_3^- + 2e^- + 2H^+ \rightarrow NO_2^- + H_2O \tag{4.2a}$$

$$NO_2^- + 2e^- + 2H^+ \rightarrow NO^- + H_2O \tag{4.2b}$$

$$NO^- + 2H^+ \rightarrow N_2O + H_2O \tag{4.2c}$$

$$N_2O + 2e^- + 2H^+ \rightarrow N_2 + H_2O \tag{4.2d}$$

$$NO_3^- + NO^- + 2e^- + 6H^+ \rightarrow N_2O + 3H_2O \tag{4.2e}$$

$$NO_2^- + NO^- + 2e^- + 4H^+ \rightarrow N_2O + 2H_2O \tag{4.2f}$$

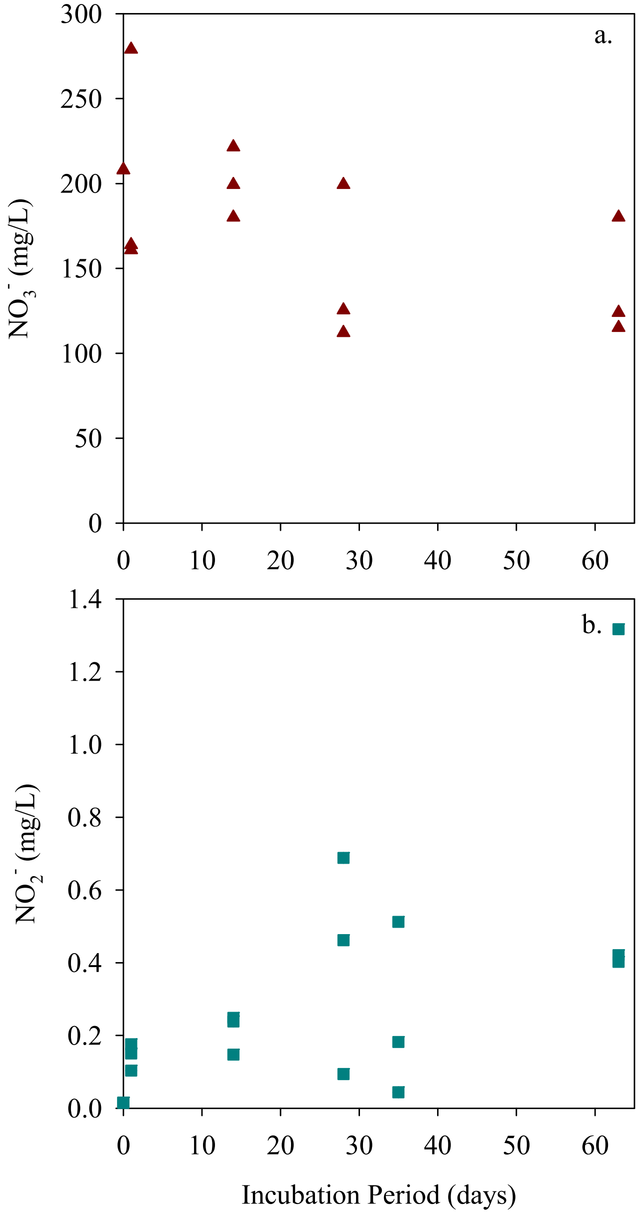

Figure 4.4: NO_3^- (a) and NO_2^- (b) concentrations in Active treatment replicates over the course of the 63-day incubation period.

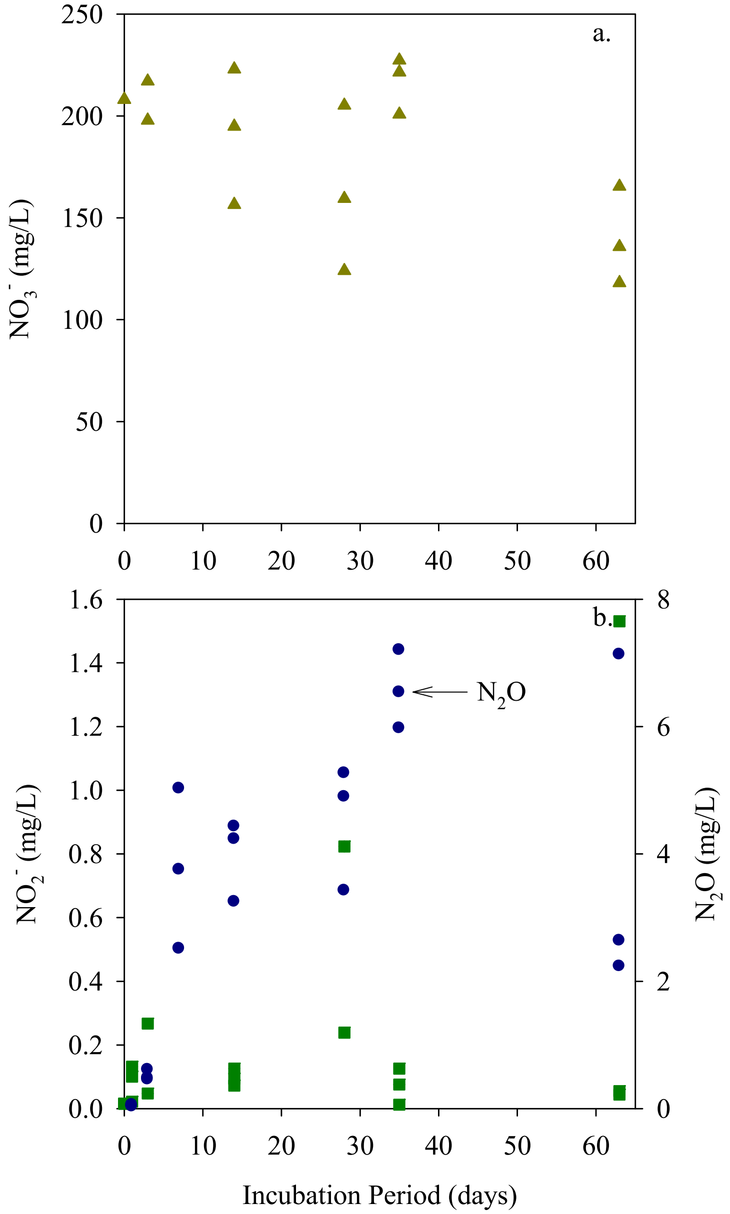

Figure 4.5: NO_3^- (a), NO_2^- and N_2O (b) concentrations in Active C_2H_2 treatment replicates over the course of the 63-day incubation period

As much as 9 µmol N_2O were produced compared to 60 µmol NO_3^- consumed in the Active C_2H_2 treatment following 63 days of incubation, resulting in a molar ratio of 7:1 as per equation (4.3) below.

$$C_7H_{8(aq)} + 7.2NO_3^-{}_{(aq)} + 7.2H^+{}_{(aq)}\ 3.6N_{2(g)} + 7CO_{2(g)}\ 7.6H_2O_{(l)} \qquad (4.3)$$

The measured relationship between NO_3^- (reactant) and N_2O (product) far exceeds the stoichiometric NO_3^- demand determined from equations (4.2e) and (4.2f). Discrepancies in mass balance ratios between

NO_3^- consumed and N_2O produced may be attributed to incomplete intermediate denitrification reaction sequences (NO_2^- and NO^-) and the inability of the acetylene block technique to completely inhibit transformation to N_2. The amount of toluene present in the microcosm solution was approximately 1 mg/L. Toluene is readily degraded under nitrate-reducing conditions. The application of elevated concentrations of NO_3^- (265 mg/L) may lead to accumulation of NO_2^-, which can also be toxic to nitrate reducing bacteria (Jorgensen et al., 1991).

The utilization of NO_3^- in the microbial active microcosm units followed an approximate zero-order reaction, where the rate coefficient k_{NO3}^- is independent of the concentration of nitrate. The denitrification rate was determined using the following relationship described in equation (4.4):

$$[NO_3^-]_t = -kt + [NO_3^-]_o \tag{4.4}$$

Where k is the zero-order denitrification rate, $[NO_3^-]_t$ is the concentration of nitrate at a specific time and $[NO_3^-]_o$ is the initial concentration of nitrate. Average zero-order denitrification rate constants determined from the Active and Active C_2H_2 treatments were similar, where $k_{NO3\text{-}Act} = 1.1 \pm 0.3$ mg/L/day and $k_{NO3\text{-}Act\text{-}C2H2} = 1.1 \pm 0.2$ mg/L/day. See Figure 4.6. Utilization of NO_3^- in a microaerophilic microcosm spiked with gasoline constituents yielded a zero-order rate coefficient of 0.4 mg/L/day (Barbaro, 1999). Laboratory estimates often tend to overestimate microbial rates of degradation in some groundwater systems (Chapelle & Lovley, 1990), whereby NO_3^- utilization in the field setting may not occur as effectively. The consistent, linear accumulation of N_2O observed in Figure 4.5b provides strong evidence to support the validity of the acetylene block technique to measure rates of denitrification (Groffman et al., 2006).

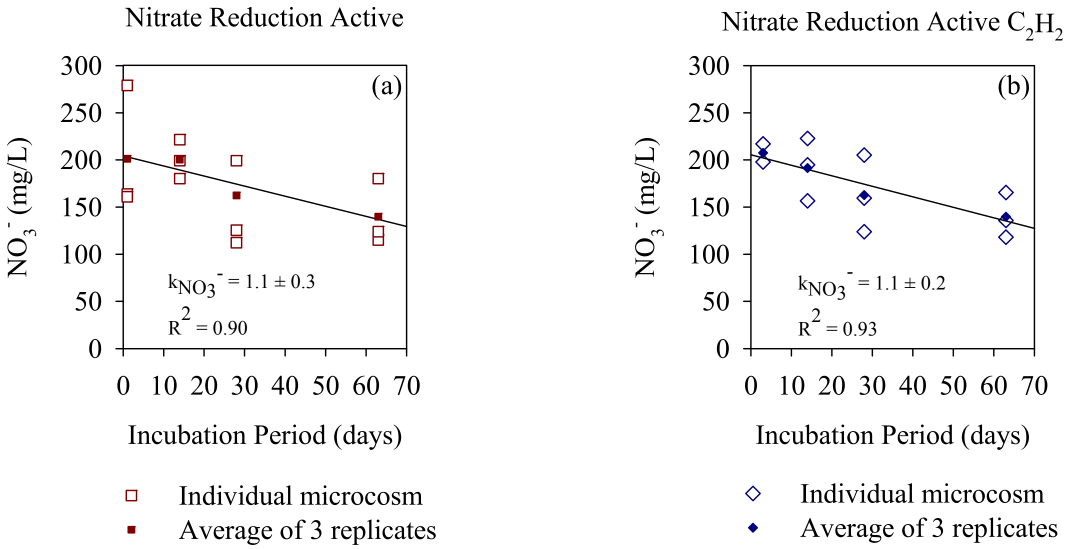

Figure 4.6: Pseudo zero-order average denitrification rate constants, k_{NO3-} calculated for Active (a) and Active C_2H_2 (b) treatment replicates. An estimated denitrification rate k_{NO3} = 1.1 ± 0.3 mg/L/day (6.3±1.5 mmol/L/yr or 0.06 ± 0.01 mg/day) was determined for the Active treatment and a rate of k_{NO3} = 1.1 ± 0.2 mg/L/day (6.5±1.2 mmol/L/yr or 0.06 ± 0.01 mg/day) was determined for the Active C_2H_2 treatment.

4.4 Interpretation of BTEXTMB Biodegradation

4.4.1 Nitrate Utilization

Throughout the course of the 63 day microcosm experiment, NO_3^- utilization was coupled to BTEXTMB degradation and the production of intermediate denitrification products NO_2^- and N_2O. The measured increase in N_2O produced is consistent with results of an anaerobic microcosm experiment involving a mixed microbial community, where relative NO_3^- reductase activity is low during the initial stages of anaerobic incubation and increases in response to prolonged exposure (20-40 hrs) (Holtan-Hartwig et al., 2000).

Denitrification occurred simultaneously with the oxidation of select aromatic hydrocarbons in both the Active and Active C_2H_2 treatments. Evidence supporting that nitrate reduction was linked to the oxidation of organic contaminants include the consumption of NO_3^- and production of intermediate denitrification products NO_2^- and N_2O (only measured in Active C_2H_2 treatment) accompanied by loss of contaminant mass. A summary of the average declining concentrations of BTEXTMB and NO_3^- for the

Active and Active C_2H_2 treatments compared to the Control are presented in Figures 4.7a and 4.8a. No significant changes in NO_3^- and BTEXTMB concentrations were observed in the inert Control treatments.

The stoichiometric relationship derived for the complete mineralization of BTEXTMB through denitrification is governed by equation 4.4

$$C_{82}H_{98} + 85.2NO_3^- + 85.2H^+ \rightarrow 42.6N_2 + 82CO_2 + 91.6H_2O \qquad (4.4)$$

After 63 days of incubation, approximately 3.4 mg (55 µmol) and 3.7 mg (60 µmol) NO_3^- was consumed from active and acetylene amended test units. Assuming BTEXTMB undergoes complete mineralization governed by the stoichiometric relationship presented in equation (4.4), an expected amount of 0.68 mg (0.64 µmol) and 0.75 mg (0.70 µmol) BTEXTMB would have been removed based on the mass of NO_3^- utilized for the Active and Active C_2H_2 treatments, respectively. The theoretical estimate of BTEXTMB removed yielded a larger amount compared to what was actually observed in the microcosm experiment, where relative differences were measured to be 25% and 46% lower in the Active and Active C_2H_2 treatments.

The relationship between the molar amounts of NO_3^- consumed to BTEXTMB degraded for both treatments is illustrated in Figure 4.7b and 4.8b, respectively. In both microbial active microcosms, the general overall trend for the averaged test replicates is that the amount of NO_3^-consumed and NO_2^- and N_2O produced increases over time (Figures 4.7c and 4.8c).

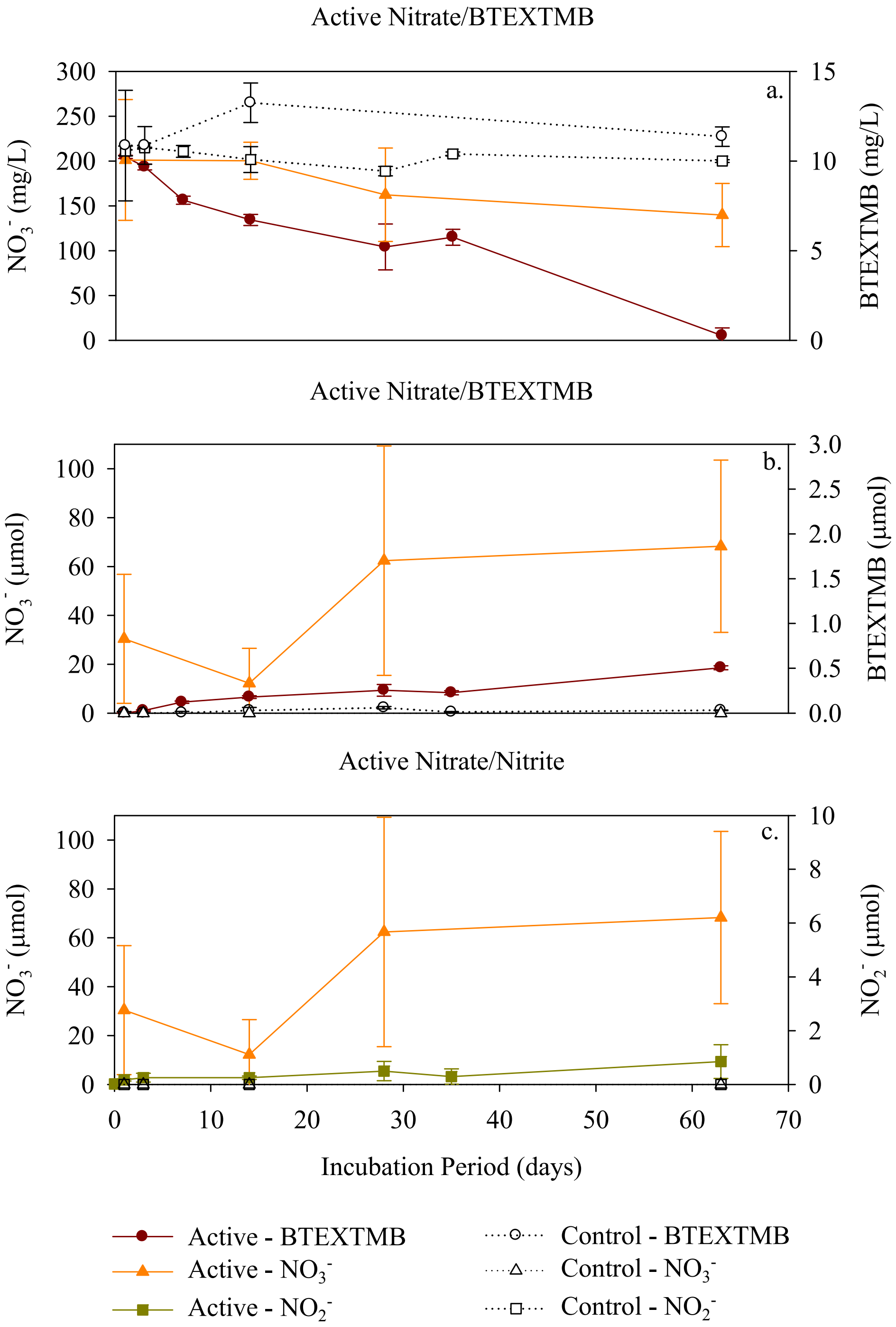

Figure 4.7: BTEXTMB, NO_3^- and NO_2^- concentration evolution over time in Active and Control treatments. BTEXTMB concentrations decrease in relation to decreasing nitrate concentrations. Cumulative nitrate reduced and BTEXTMB degraded accompany NO_2^- production in the Active treatment only.

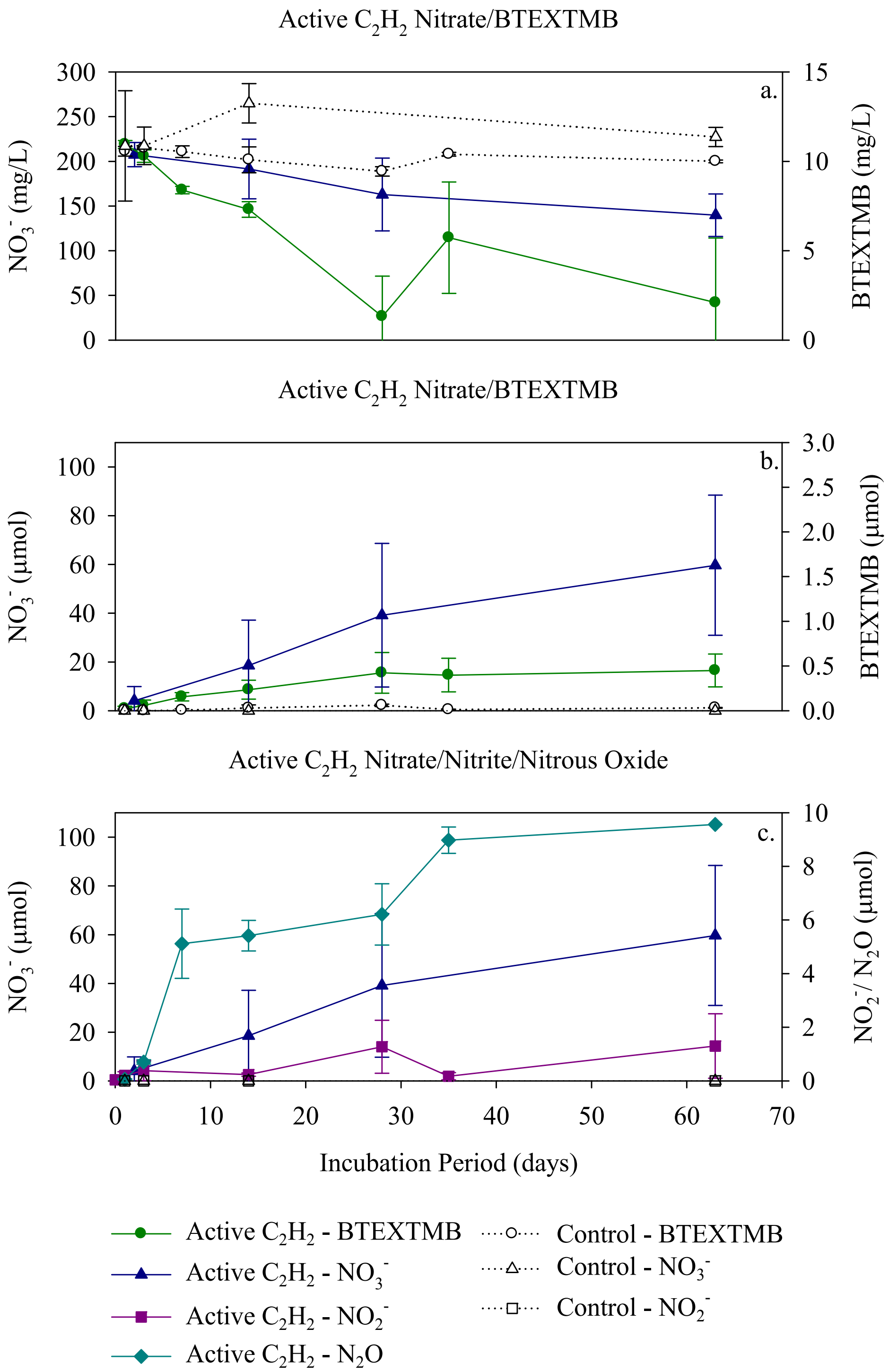

Figure 4.8: NO_3^- consumed, BTEXTMB, NO_2^- and N_2O molar quantities evolution over time in Active C_2H_2 and Control treatments. BTEXTMB concentrations decrease in relation to decreasing nitrate concentrations. Cumulative NO_3^- reduced and BTEXTMB degraded accompany nitrite production in the Active C_2H_2 treatment only.

Nitrate utilization, production of intermediate products and consumption of BTEXTMB was relatively consistent between the Active and Active C_2H_2 amended treatments. An average of 55 μmol NO_3^- were utilized in the Active treatment, resulting in 0.9 μmol NO_2^- produced and the approximate removal of 0.5 μmol of BTEXTMB compared to approximately 60 μmol NO_3^- consumed in the Active C_2H_2 treatment, resulting in the production of 0.7 μmol $NO_2^-$and 9.6 μmol N_2O and removal of 0.4 μmol of BTEXTMB. Although the C_2H_2 amendment yielded similar BTEXTMB removal compared to the active treatment, the presence of C_2H_2 appears to consistently inhibit the ability of the microbes to mineralize the organic contaminants, especially those consisting of the F3(nC_{16}-nC_{34}) fraction where limited to no biodegradation took place (Table 4.3).

The observed ratio of NO_3^- consumed to BTEXTMB degraded demonstrates a higher NO_3^- demand than described by the stoichiometric relationship, which does not include potential NO_3^-loss from competing electron acceptors such as SO_4^{2-} and dissolved iron present in the test solution or oxidation of aromatic hydrocarbons from alternative EAs. The limitation of denitrification in the metabolism of gasoline constituents may result in the persistence of groundwater and residual contaminants.

Nitrate would have been preferentially utilized following the transition from microaerophilic to anaerobic conditions after day 3. The importance of NO_3^- reduction is dependent on the NO_3^- supply and availability of electron donor, BTEXTMB. Degradation of the gasoline constituents of toluene, ethylbenzene, the xylenes, and 1,2,3-trimethylbenzene but not benzene was reported under NO_3^- utilization by Hutchins et al. (1991). Low-molecular-weight PAHs such as naphthalene can be completely degraded under denitrifying, nitrate-excess conditions (Mihelcic & Luthy, 1988) which is consistent with the results of the microcosm experiment (Fig. 4.3b,c). The observed utilization of aromatics, is consistent with previous studies that demonstrated toluene, ethylbenzene, and m-xylene to be completely degraded after 8 days, while o-xylene following 75 days where benzene was recalcitrant (Reinhard et al., 1995).

4.4.2 Utilization of Alternative TEAs

Despite efforts to maintain an anaerobic environment for the microcosms the test solution was subject to atmospheric O_2 during the dispensing and mixing phases which rendered the conditions of the microcosm microaerophilic. The microbial activity likely initiated as aerobic respiratory growth until O_2 was consumed, allowing the organisms to shift to denitrifying metabolism. A significant portion of aromatic hydrocarbon mineralization occurred under denitrifying conditions due to the large supply of NO_3^- TEA present in the microcosm compared to the alternative TEA DO. Dissolved oxygen measured in the active microbial treatments was depleted to below 2 mg/L after within 3 days of incubation in the anaerobic chamber.

The depletion of gasoline constituents via the removal of BTEXTMB in the Active and Active C2H2 amended microcosms from microbial activity was apparent. These findings are consistent with results for mixed electron acceptor conditions, where microbes are capable of degrading benzene, toluene, ethylbenzene, and naphthalene, with 2 mg/L DO and NO_3^- concentrations in excess of 150 mg/L, while inhibited at low oxygen levels (< 2 mg/L) with the exception of toluene (Wilson, Durant, & Bouwer, 1995). Degradation of contaminants would have occurred under limited aerobic conditions in the presence of O_2, which is more energetically favourable compared to NO_3^-in the oxidation of organic compounds. Edwards et al. (1992) reported that ethylbenzene and benzene tend to be degraded last under anaerobic conditions due to the presence of more suitable substrates as toluene and m,p-xylene resulting in a lag time before degradation occurs. The results of Edwards et al. (1992) differ significantly from what was observed in both Active and Active C_2H_2 microcosm treatments in regards to both benzene and ethylbenzene, most likely attributed to mineralization by O_2 serving as an alternative TEA under the microaerophilic conditions that existed during the early stages of the microcosm experiment.

Under O_2 depleted conditions, denitrification would have been carried out under anaerobic conditions accompanied by the possible reduction of SO_4^{2-} in the degradation of contaminants, which is naturally occurring in the hydrogeological system present at the Site. Indications that microbial utilization of electron acceptors other than NO_3^- is apparent considering only 9% and 22% of benzene remained in the Active and Active C_2H_2 treatments following 63 days of incubation. Benzene readily undergoes metabolism under aerobic conditions (e.g. Smith, 1990; Gibson & Subramanian, 1984) and anaerobic sulphate reducing conditions (e.g. Edwards & Grbić-Galić, 1992; Lovely et al., 1995), although removal may be slow, incomplete or subject to lag times (Ward et al., 1980).

Approximately 0.57 mg of BTEXTMB was available as a carbon and energy source to microbial populations in each microcosm. The highest DO observed in active and acetylene amended active microcosms was 2 mg/L O_2, resulting in about 3.4 µmol O_2 available to mineralize 0.03 µmol of BTEXTMB, roughly equivalent to 5% according equation (4.6):

$$C_{82}H_{98} + 106.5O_2 \rightarrow 82CO_2 + 49H_2O \qquad (4.6)$$

Another alternative electron acceptor, sulphate, was also present in the Site groundwater used for the test solution at an average concentration of 12 ± 5 mg/L. An estimated 7 µmol (0.66 mg) of SO_4^{2-} was present in each microcosm that could have been utilized in the oxidation of 0.12 µmol (0.128 mg) BTEXTMB (up to 22%), assuming similar stoichiometric ratios were applied in the oxidation of toluene presented in equation (4.7)

$$C_7H_8 + 4.5SO_4^{2-} + 3H_2O \rightarrow 7HCO_3^- + 2.25H_2S + 2.25\ HS^- + 0.25H^+ \qquad (4.7)$$

SO_4^{2-}concentrations consistently remained variable in the microcosms in all treatments, including the control, leading to a significant amount of uncertainty associated with the validity of the SO_4^{2-} concentrations measured. Apart from the lack of declining SO_4^{2-}concentrations, evidence to support sulphate reduction of aromatic hydrocarbons may be apparent as a result of the formation of visible iron sulphides present in 75% of the Active replicates and 25% of the Active C_2H_2 replicates on day 63 only.

4.5 Microcosm Summary

Biodegradation of BTEXTMB, F1-F3 fractions and TPH occurred in microcosms equipped with a mixed indigenous microbial source obtained from the study area. The acetylene block microcosm experiment was successful in establishing that the organisms were capable of utilizing nitrate in the metabolism of petroleum hydrocarbons. In general, the consumption of NO_3^- coincided with reductions in the mass of BTEXTMB present in the microcosm units, in addition to the observed increase in the production of denitrification intermediate products NO_2^- (Active and Active C_2H_2) and N_2O (Active C_2H_2 only). The findings of the microcosm experiment confirm that the application of NO_3^- to enhance the microbial degradation of petroleum hydrocarbons at a larger scale field setting is a suitable remedial approach to target contaminants at residual saturation in the anaerobic aquifer present at the Site.

Chapter 5: Residual Zone Treatment System Design

5.1 Remediation Approach

Several pulses consisting of known mass of non-reactive (Br^-) and reactive tracer (NO_3^-) solution were released into the anaerobic aquifer. The pulse solution was allowed to drift under natural gradient conditions to target residual contaminants distributed within Unit 3 (sand and gravel) and Unit 4 (sand). Three dimensional monitoring of the Br^- tracer plume was carried out using an extensive multilevel well network downgradient of the injection well. The analysis of the Br^- tracer monitoring determined the variability of hydraulic conductivity and contaminant distribution, as previously discussed in Chapters 2 and 3.

A series of field tracer injections characterized the transport and utilization rates of NO_3^- in a portion of the residual petroleum hydrocarbon impacted zone. The tracer test solution was delivered by a consecutive series of injections with the purpose of providing a continuous supply of TEA available to the indigenous microbial populations. The tracer injection test was designed to:

1) Evaluate the delivery of remedial solution to distinct geological layers of different permeability
2) Estimate denitrification rates using tracer breakthrough curves (BTCs) in a heterogeneous aquifer, and
3) Evaluate the removal of residual saturation contaminants in the study area using soil coring techniques and post-treatment groundwater sampling to evaluate the dissolved phase.

5.2 Target Remediation Zone

The selected target treatment zone was based on the aquifer composition, distribution of residuals, and the vertical extent of the seasonal saturated zone. The target zone is located 305 to 303 m AMSL (6.2 to 8.2 meters below ground surface). The remedial system design established delivery of the remedial solutions to Unit 4 situated below the seasonal minimal water table in an area where residuals are present. Residuals serve as a long term source of contamination and contribute to vapour phase and dissolved phase plumes, thus the residual zone was targeted for biostimulation to enhance in situ bioremediation. The removal of contaminant source mass is advantageous in remediation technologies as there is a reduction in the mass of contaminants discharged to the plume (e.g. Rao et al., 2001).

Additional soil coring (400 series cores) confirmed that Unit 4 is to some extent continuous at the same depth down gradient and comes into contact with similar materials throughout the study area, as indicated by the borehole logs presented in Appendix B. Investigating sediment characterization revealed that Unit 4 is subject to small scale heterogeneities inferred from hydraulic conductivity estimates carried out by grain size analysis. Therefore, Unit 4 was selected as a suitable treatment zone to promote the effective delivery and performance of the remedial solution within the target residual zone as heterogeneities in aquifer sediments can constrain hydrogeologic transport of remedial additions and biogeochemical reactions (e.g. Cozzarelli et al., 1999).

As discussed in Chapter 3, it was challenging to determine the complex distribution of residual contaminants in the subsurface. The vertical and spatial distribution of BTEXTMB soil concentrations indicate that the majority of the aquifer materials investigated to depths between 310 and 302 m AMSL (1 and 9 mbgs) contain immobile NAPL phase. The presence of NAPL is inferred based on the soil concentrations exceeding 13 mg/kg (wet soil), with the value determined, using the Feenstra et al. method (1991) while mobile NAPL is inferred for BTEXTMB exceeding 3,000 mg/k (wet soil) as previously discussed. Measured concentrations did not surpass 3,000 mg/kg, however NAPL recovered in the field reveal that seasonal re-distribution of NAPL is likely occurring under dynamic hydrogeologic conditions.

To satisfy the requirements that the remedial solution be transferred below the water table at any given time and administered within stratigraphic Unit 4, BTEXTMB soil extract concentrations in BH-301 and BH-302 retrieved in fall 2007 were then examined to assess the distribution of contaminants. The targeted depth interval selected based on the aforementioned criteria was between

305 and 303 m AMSL, considering sandy Unit 4 and distributions of BTEXTMB in BH-301 and BH-302 were relatively consistent between the two boreholes. July 2009 coring results of BH-501 are also in agreement with BH-301 and BH-302 in regards to stratigraphy and contaminant distribution. A select cross-section of the targeted treatment zone is represented in Figure 5.1, where the proposed aquifer materials subject to the delivery of remedial solution are identified in relation to stratigraphic units and BTEXTMB distribution in the subsurface.

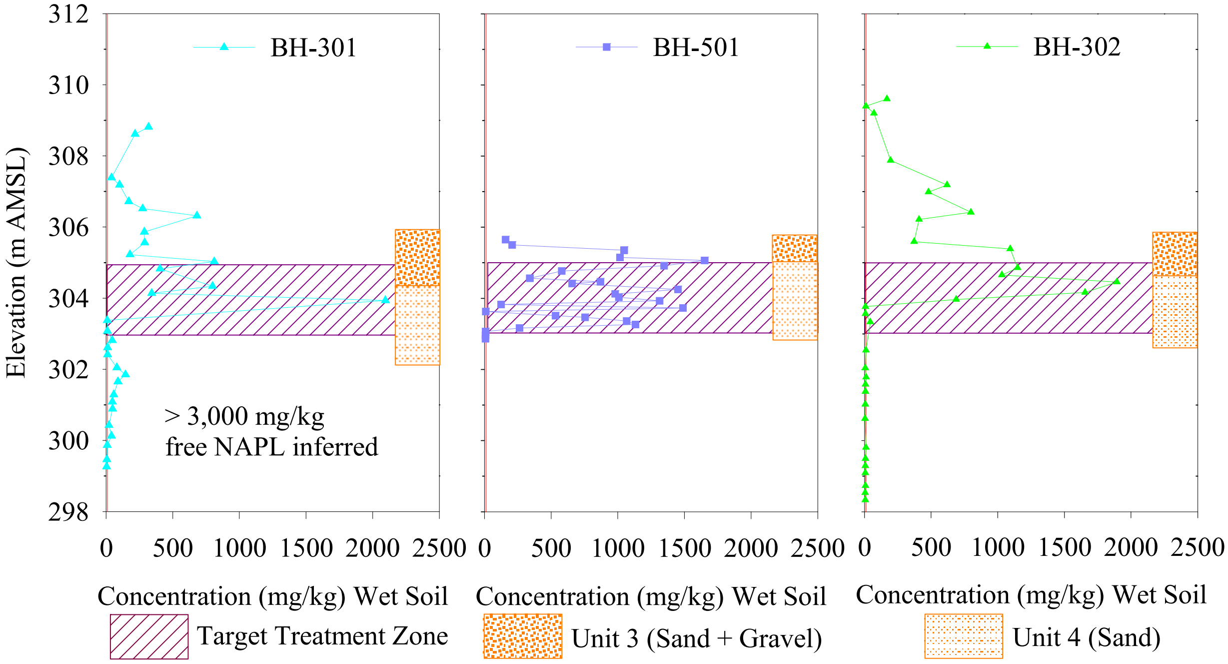

Figure 5.1: Target residual zone is between 305 to 303 m AMSL (6.2-8.2 m bgs).

5.3 Remediation System Design

The design of an in situ remediation system allowed for a large volume of remedial solution to be delivered to target zone containing residual phase petroleum hydrocarbon contaminants. The injection solution was amended with NO_3^- as the TEA in the biodegradation of hydrocarbons and Br^- as a conservative tracer. Nitrate is readily transported in the groundwater system; however, it is subject to biological uptake and degradation by indigenous microbial populations. The addition of a

TEA to an aquifer enhances in situ biodegradation of petroleum hydrocarbons, by providing the microbes with a sustainable energy source to promote cell maintenance and growth of the microbial population. Microbial mediation of the metabolism of organic compounds using a TEA results in approximately 10-50% of the energy released from the redox process being put towards synthesizing new cells and maintaining cells already formed (e.g. Pirt, 1975). The delivery of the TEA to Unit 4, the targeted aquifer zone, was evaluated using tracer breakthrough behavior measured within the injection well and remediation monitoring network using discrete multilevel sampling wells screened within the hydrogeologic units of interest.

Tracer tests are well documented and useful as tools for the estimation of biodegradation rate constants and determining transport parameters in the aquifer (e.g. Schreiber & Bahr, 2002). Bromide behaves conservatively in the subsurface flow regime and is not subject to natural attenuation by adsorption, biodegradation or precipitation and has been successfully applied to field tracer experiments dealing with physical and biological characterization of aquifers (e.g. Haggerty et al., 1997).

5.3.1 Injection Well

Injection well MW-501 is comprised of a 0.051 m inner diameter PVC well casing equipped with a 2 m slotted screen from 303 to 305 m AMSL (6.2 to 8.2 m bgs) penetrating Unit 4. The screen length was designed to fully penetrate Unit 4, based on borehole logs and the interpolation of aquifer materials between BH-301 and BH-302. Coring of MW-501 revealed that Unit 4 is relatively continuous within the targeted aquifer zone. Additional borehole log data with subsurface stratigraphy sediment types are included in Appendix B. Challenges encountered during the installation of MW-501, included sand bridging in the borehole and the collapse of native material around the well screen. The injection well MW-501, was equipped with a 2 m screen interval in native soil enclosed within a 3.2 m sand pack, which extended 1.2 m above the top of the well screen and sealed to the ground surface with bentonite clay. When considering the construction of the well, the injectate distribution was assumed to occur throughout the entire vertical extent of the well screen and sand pack (3.2 m or 306 to 302.8 m AMSL). The delivery interval includes Unit 3 (sand and gravel) and Unit 4 (sand) materials.

5.3.2 Monitoring Well Network

A network of one upgradient (MW-301), nine downgradient multilevel wells (MW-302, MW-303, MW-304, MW-401, MW-402, MW-403, MW-404, MW-405 and MW-406) and an additional four downgradient monitoring wells (MW-601, MW-603, MW-602 and MW-604) were used to determine the spatial distribution and tracer breakthrough periods within specific stratigraphic layers. A plan view distribution of the injection well and monitoring well network is presented in Figure 5.2.

Downgradient multilevel monitoring wells are screened within aquifer Units 2, 3, 4 and 5. Monitoring wells are screened in aquifer materials approximately 1.5 m above the target zone and 2 m below the injection well screen. Multilevel wells were used to evaluate the vertical distribution of the delivery of the remedial tracer solution to different hydrogeologic units of variable hydraulic conductivity and contaminant distributions. Borehole logs prepared by SNC-Lavalin during the installation of monitoring wells are found in Appendix 2. Information is also included pertaining to sediment descriptions, formations screened and well construction materials.

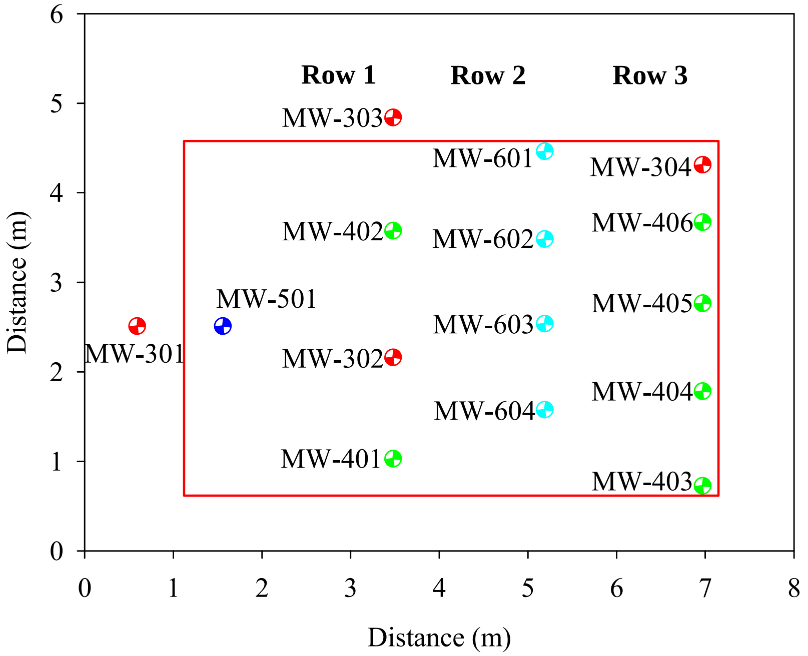

Figure 5.2: Plan view of in situ remediation injection well (MW-501), target remedial zone (red box) and monitoring network (MW series 300, 400 and 600).

Multilevel well MW-301 is located 1 m upgradient from the injection well. Downgradient monitoring wells are organized in a series of 3 rows, located approximately 2 m (Row 1), 3.7 m (Row 2) and 5.4 m (Row 3) from MW-501, as represented in Figure 5.3. Spacing between monitoring wells within a select row ranges between 1 to 1.5 m apart. The wells are closely spaced in order to minimize the potential of the injected slug passing in between two monitoring points and not being traced. The close well-spacing is also useful in identifying the trajectory of the injected slug and delineating the horizontal distribution of the tracer immediately following the injection and over time under the transient hydrogeologic conditions present at the Site. The spatial and vertical distribution of the monitoring network in relation to the injection well and the maximal and minimal groundwater elevations encountered within the duration of the test are depicted in Figure 5.3.

The 300 series multilevel monitoring wells, installed in November 2007, are part of the initial site characterization. The wells consist of a 0.0127 m ID standpipe center stock surrounded by eight

0.0064 m ID PVC tubing terminating in a 0.2 m screen at a 1 m interval between 306.3 to 302.3 m AMSL (ports 5-9).

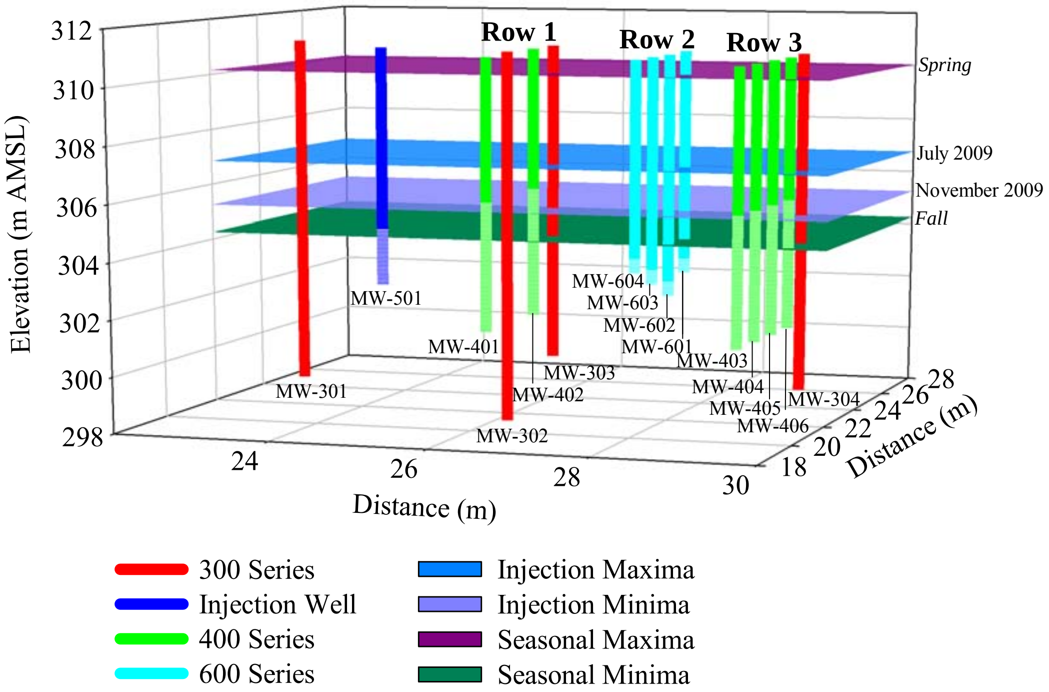

Figure 5.3: Remediation network plan including injection well (MW-501) and monitoring wells. Groundwater elevation planes are shown at various times. Groundwater flow direction occurs from left to right.

The 400 series monitoring wells were installed in July 2009 specifically for the monitoring the distribution of the injected tracer slug. The multilevel bundles are constructed of 0.0191 m ID PVC pipe centre stock surrounded by eight 0.0111 m ID multilevel ports, each terminating in a 0.5 m screened interval from approximately 306 to 301.5 m AMSL (5 to 9.5 m bgs).

The 600 series wells are comprised of a 0.0254 m ID PVC pipe equipped with a 0.5 m screen and were installed in October 2009 in sandy Unit 4 as part of another research program. The monitoring of the distribution of the remedial solution was conducted with the 600 series wells during subsequent injections.

5.4 Enhanced, In Situ Denitrification Treatment System

The target residual contaminant zone consists of an anaerobic environment to which the necessary reduced conditions for denitrification to occur exist. Nitrate in drinking water supplies is regulated by the Ontario Drinking Water Quality Standards (ODWQS), where the maximum contaminant level (MCL) for nitrate (as nitrogen, NO_3-N) is 10 mg/L NO_3-N as (MOE, 2003). A certificate of approval from the Ontario Ministry of Environment (MOE) was granted in order to permit the application of NO_3^- at concentrations 2-6 times ODWQS.

Given that the addition of NO_3^- at levels exceeding regulation was introduced into the petroleum impacted environment, it was assumed that the NO_3^- would be readily degraded under the anaerobic conditions, as a sufficient supply of dissolved, residual and free-phase petroleum hydrocarbons was present to serve as electron donors. Sentinel wells located downgradient from the injection well, within the monitoring network, were monitored for NO_3^- to evaluate the potential migration of a NO_3^- contaminant plume beyond the property limits in the event that significant denitrification in the contaminated aquifer was not apparent.

5.4.1 Site Suitability

The application of nitrate-amended treatment water to enhance anaerobic biodegradation of residual PHCs is a suitable technology given the physical and geochemical properties of the aquifer materials. Cunningham et al. (2001) describe typical site conditions that are suited to the biostimulation of indigenous microbial populations with the addition of a TEA to promote the oxidation of organic contaminants, including:

1) Anaerobic groundwater conditions exist at the Site with a presence of anaerobic bacteria;
2) Supply of electron acceptor and/or removal of inhibitors are limiting
3) Aquifer solids are sufficiently permeable, and
4) Additional lab and field data provide evidence to support technology.

Site characterization involving geochemical analysis of groundwater and aquifer material permeability testing indicate that the Site meets the criteria for enhanced in situ bioremediation of BTEX contaminated groundwater. Anaerobic groundwater conditions are present within the study area and exist strictly in the petroleum impacted areas, where the concentration of TEAs: dissolved O_2, NO_3^- and SO_4^{2-} are significantly depleted compared to background conditions as previously discussed in Chapter 2. Surface water infiltration can introduce O_2, NO_3^- and SO_4^{2-} into the reduced environment where they may become readily metabolized in the petroleum impacted aquifer under redox conditions. The geochemical results discussed in Chapter 2 signify that reducing conditions exist in the PHC impacted portion of the aquifer, suggesting that active aerobic microbial degradation of dissolved contaminants has taken place and anaerobic biodegradation is occurring.

Significant bacteria-mediated denitrification in the aquifer only occurs in the absence of O_2, related to the fact that most denitrifying bacteria are facultative aerobes and have the ability to utilize both electron acceptors in metabolic processes. These bacteria are capable of readily adapting to both aerobic and anaerobic conditions. The presence of denitrifyers in aquifers was not targeted for analysis as it was assumed that a sustainable population was present within the research area given the geochemical and microbiological data available for the Site.

The concentration of nitrate added (90 – 265 mg/L NO_3^-) was far in excess of other naturally occurring TEAs in the petroleum impacted region of the aquifer in order to sustain the preferential metabolism of NO_3^- as a terminal electron acceptor in the oxidation of organic contaminants where 0.3 to 1.4 mg/L O_2 and 1 to 2 mg/L SO_4^2 have been historically measured at MW-103 (SNC Lavalin, 2008). Upgradient concentrations of 7.5 to 14 mg/L NO_3-N have been measured by SNC Lavalin in MW-109 which may be indicative of how much TEA is available naturally at the Site, whereas concentrations below detection limit have consistently been measured in the petroleum impacted aquifer.

The targeted aquifer sediments predominantly consist of a sandy layer, Unit 4, where K = 3.1×10^{-5} m/s) with a small portion of the overlying sand and gravel layer (Unit 3, K = 6.9×10^{-5} m/s) in the screened portion of the injection well. The aquifer sediments are sufficiently permeable to transmit a remedial solution amended with TEA to the contaminated zone; a requirement according to Cunningham et al. (2001). The injection solution is preferentially transported in higher permeable aquifer units and may have a shorter residence time in these areas compared to less conductive units. The issue of heterogeneity was not recognized by Cunningham et al. (2001) and is a key issue followed in this experiment. Lower permeability (but still very permeable) units of the heterogeneous aquifer are of interest in the assessment of delivery of the treatment solution. The presence of anaerobic microbial populations at the Site meet the criteria specified by Cunningham et al. (2001). Iron and sulphate reducing bacteria were identified during microbiological groundwater sampling conducted by SNC-Lavalin in 2007 in the reduced study area conditions. As discussed in Chapter 4, a microcosm study confirmed that the indigenous microbes were capable of degrading petroleum hydrocarbons utilizing nitrate as a terminal electron acceptor.

5.4.2 Mass of Contaminants in the Targeted Source Zone

A remedial zone was selected based on the understanding of the spatial distribution of contaminants determined during the analysis of the soil extraction concentrations obtained during the November 2007 and July 2009, prior to the coring activities associated with the remedial solution injections. The remedial zone consisted of a 48 m^3 volume of aquifer materials (6 m length x 4 m wide x 2 m thick). The zone of interest included aquifer materials between elevations 305 and 303 m AMSL and encompassing wells MW-501; MW-401, MW-402, MW-302 (Row 1); MW-601, MW-602, MW-603 and MW-604 (Row 2) and MW-403, MW-404, MW-405, MW-406 and MW-304 (Row 3) as illustrated in Figure 5.2 and Figure 5.8.

The total mass of contaminants located within the target zone (M_T) was estimated using total soil extract concentrations determined during the two soil coring events, prior to the remedial injections.

The mass of contaminants M_j, for each core was determined by summing the product of each individual sample soil extract concentration C_{ti}, with the inferred core sample thickness ($h_{i,j}$), over all *n* core segments. The Mj for each core is assumed constant over an area extending to half the distance to the nearest core, A_j, the Thiessen area. M_T is then calculated using equation (5.1):

$$M_T = \sum_{j=1}^{n} \mathrm{A_j} \rho_\mathrm{m} \left(\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{C_{ti,j}}\ \mathrm{h_{i,j}} \right) \tag{5.1}$$

An estimated 600 kg of total petroleum hydrocarbons consisting of approximately 126 kg of total BTEXTMB remains within the targeted source zone based on the results of the soil extract concentration investigations after applying equation (5.1).

5.4.3 Mass of Nitrate Required

The remediation system was designed and implemented to specifically target the mass reduction of residual toluene in the aquifer, while evaluating the success of the addition of NO_3^- to biostimulate the degradation of petroleum hydrocarbons. Soil core results were analyzed during preliminary site investigations to delineate a study area and target the delivery of remedial solution to residual saturation aquifer materials. Saturated hydrocarbons are readily biodegraded in groundwater under nitrate-reducing conditions (Holliger & Zehnder, 1996), however the target contaminants of interest for biodegradation are BTEXTMB due to the associated health risks.

A total of 600 kg of TPH (F1-F3), including 126 kg (BTEXTMB was inferred within the target remedial zone from interpretation of soil coring results as previously described in Section 5.4.2. Approximately 18 kg or 193 moles of toluene was present in the study area prior to the application of remediation efforts. The stoichiometry of the biologically mediated denitrification reaction using toluene as the electron donor is presented as followed in equation (5.2):

$$C_7H_{8(aq)} + 7.2NO_3^-{}_{(aq)} + 7.2H^+{}_{(aq)}\ 3.6N_{2(g)} + 7CO_{2(g)}\ 7.6H_2O_{(l)} \quad (5.2)$$

Assuming the reaction goes to completion, approximately 5 mg of nitrate are required to oxidize and remove 1 mg of toluene. Based on the relationship of 7.2 moles NO_3- required to degrade 1 mole C_7H_8 approximately (7.2 mol x18 mol toluene) 130 kg of NO_3 would be necessary to provide a sufficient supply of TEA to the microbes, assuming the reaction goes to completion. Considering the 600 kg of TPH contaminants present within the study area, a minimum of 3,000 kg NO_3^- would be required to degrade all the PHCs in the entire 48 m^3 source zone, assuming the degradation of TPH follows a similar nitrate demand as toluene.

5.4.4 Expected Success of Remediation System

Seasonal groundwater sampling revealed that an average of 30 mg/L total petroleum hydrocarbons (TPH) (F1-F3 fractions) is present within the study area in the dissolved phase. The dissolved phase component would provide an additional 0.46 kg of contaminant mass, requiring an additional (5 x 0.46 kg) 2.3 kg of NO_3^-. That is an insignificant TEA demand compared to the 3,000 kg demand estimated in section 5.4.3, above. This is why removal of residual NAPL was targeted, with NAPL serving as a long term source of contaminants.

A total of 3.7 kg NO_3^- was applied during the remedial efforts which served as a TEA to stimulate in situ biodegradation of petroleum contaminants, however this TEA mass was essentially insignificant compared to the mass of contaminants present. If we then assume that only monoaromatics (BTEXTMB) are degradable by denitrification, (inferred from Brown, Mahaffey, & Norris, 1993), less than 1% of the 126 kg of BTEXTMB could be biodegraded with the 3.7 kg of nitrate added in this experiment. Assuming complete mineralization of contaminants of interest based on the stoichiometric relationship discussed in equation (5.2), approximately 4% of the mass of toluene present in the residual phase could have been removed.

Realistically speaking, the anticipated amount of toluene removed within the target area is negligible and the evaluation of post-remediation success through coring and groundwater sampling are difficult to measure considering only small removal of mass of contaminants is expected.

5.5 Remediation Tracer Test Procedure

Details of the preparation of the remediation test solution and delivery to the target saturated zone are described in Appendix D. The individual injection test solution consisted of 2,000 L of municipal water spiked with 200 mg/L Br^- and 90-265 mg/L NO_3^-, to stimulate biodegradation of contaminants located in a residual NAPL zone of the aquifer. The treatment water was amended initially with 90 mg/L NO_3^- and then increased over time to 265 mg/L NO_3^-. This scheduling allowed the indigenous microbial populations to gradually acclimate to the augmented geochemical conditions. The water was obtained from the municipal supply, de-chlorinated with the application of sodium thiosulphate and then sparged with N_2 to lower dissolved O_2 to levels less than 1 mg/L. The volume of test solution injected each time was sufficient to penetrate a radial distance into the aquifer, approximately 1.9 m beyond the outer edge of the sand pack assuming penetration through the total 2 m well screen radially into sandy Unit 4 in a spherical shape. It is recognized the actual penetration is subject to aquifer heterogeneities.

A total of 12 injections (24,000 L total) were carried out over a 17 week period, from July to November 2009. A summary of the remedial tracer test details and schedule is presented in Table 5.1 The remedial solution was well-mixed and delivered into the screen of injection well MW-501below the water table at an average rate of 35 L/min using a centrifugal pump. A schematic of the test setup is presented in Figure 5.4 and cross-section of the injected slug is illustrated in Figure 5.5.

Table 5.1: Remedial Tracer Test details and injection schedule.

Injection #	Date	Volume Injected (L)	Tracer Concentration (mg/L)	Reactant Concentration (mg/L)	Test Solution Temperature (^oC)	Dissolved Oxygen (mg/L)
1	28-Jul-09	2063	200	90	20.1	<1
2	5-Aug-09	2070	200	90	19.2	<1
3	7-Aug-09	2092	200	90	19.8	<1
4	10-Aug-09	2131	200	90	20.2	<1
5	13-Aug-09	2094	200	90	20.4	<1
6	17-Aug-09	2128	200	90	23.2	<1
7	25-Aug-09	2102	200	200	19.7	<1
8	9-Sep-09	2108	200	200	19.2	<1
9	24-Sep-09	2051	200	200	nm	<1
10	15-Oct-09	2076	200	200	nm	<1
11	3-Nov-09	1950	200	200	nm	<1
12	18-Nov-09	2017	200	265	10	<1

nm – temperature not measured.

The injections were scheduled every 2 to14 days depending on the rate of loss of the Br^- tracer within the injection well and governed by the groundwater flow conditions. The injection schedule was designed to create a continuous slug of remedial solution amended with nitrate within the source zone. Groundwater was monitored within the targeted areas for the presence of the injected aquifer conservative tracer. Injections were repeated when the concentration of Br^- tracer was reduced to a 0.5 relative concentration within the injection well. Transient groundwater flow conditions at the Site drove the dilution of the conservative tracer. The conservative tracer was flushed from the injection well within 4 days. During injections 2-8 in August-early September, the tracer was flushed from the system within 1 or 2 days, but slowed as the subsequent 9-12 injections continued on into the Fall. The forced injection of the treatment solution likely enhanced dispersive mixing as a result of the higher groundwater velocity.

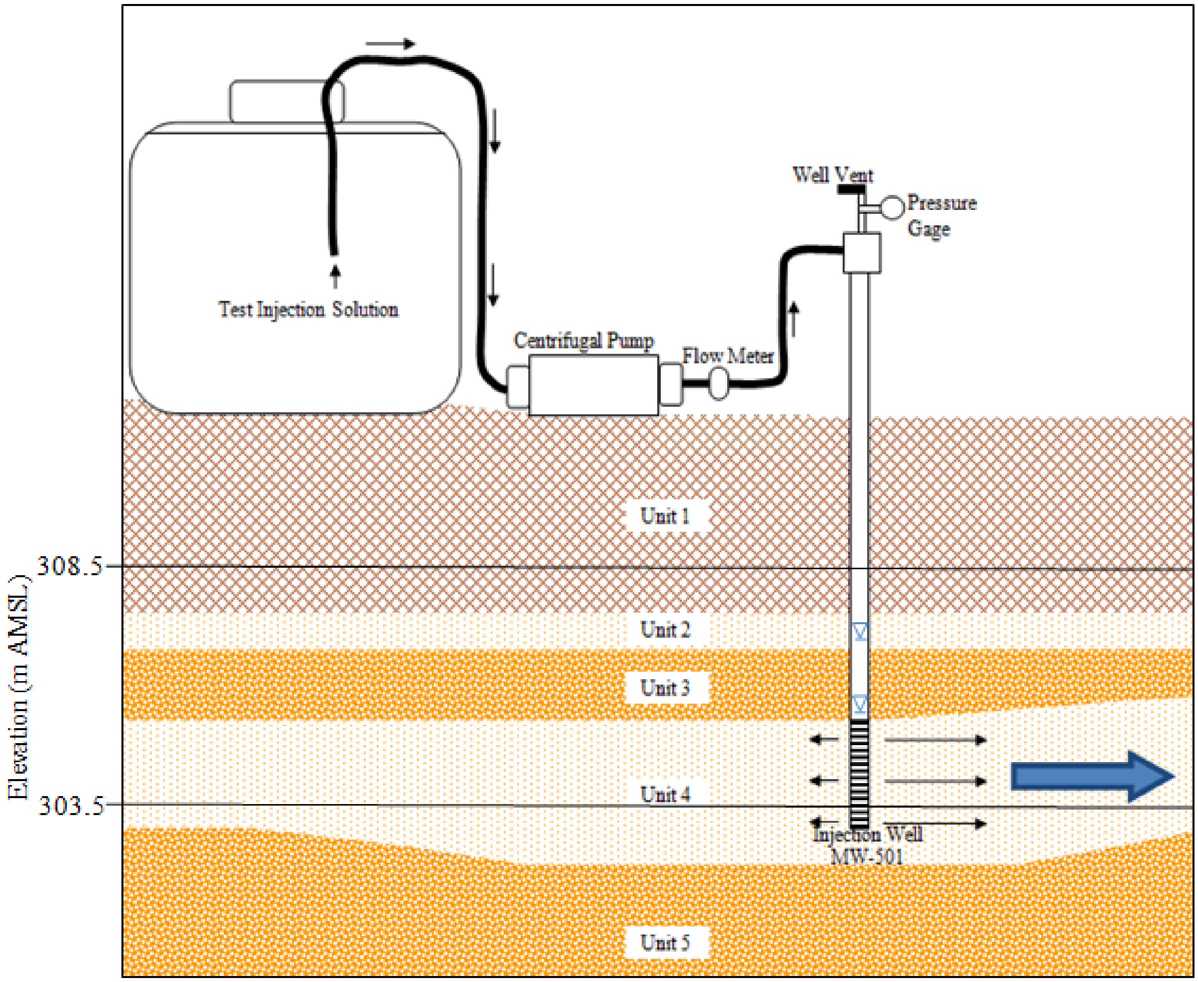

Figure 5.4: Cross-sectional view of remedial tracer test solution being injected in MW-501 including storage of prepared test solution in carboy, delivery line from centrifugal pump to well and groundwater elevation minima and maxima range throughout the series of injections.

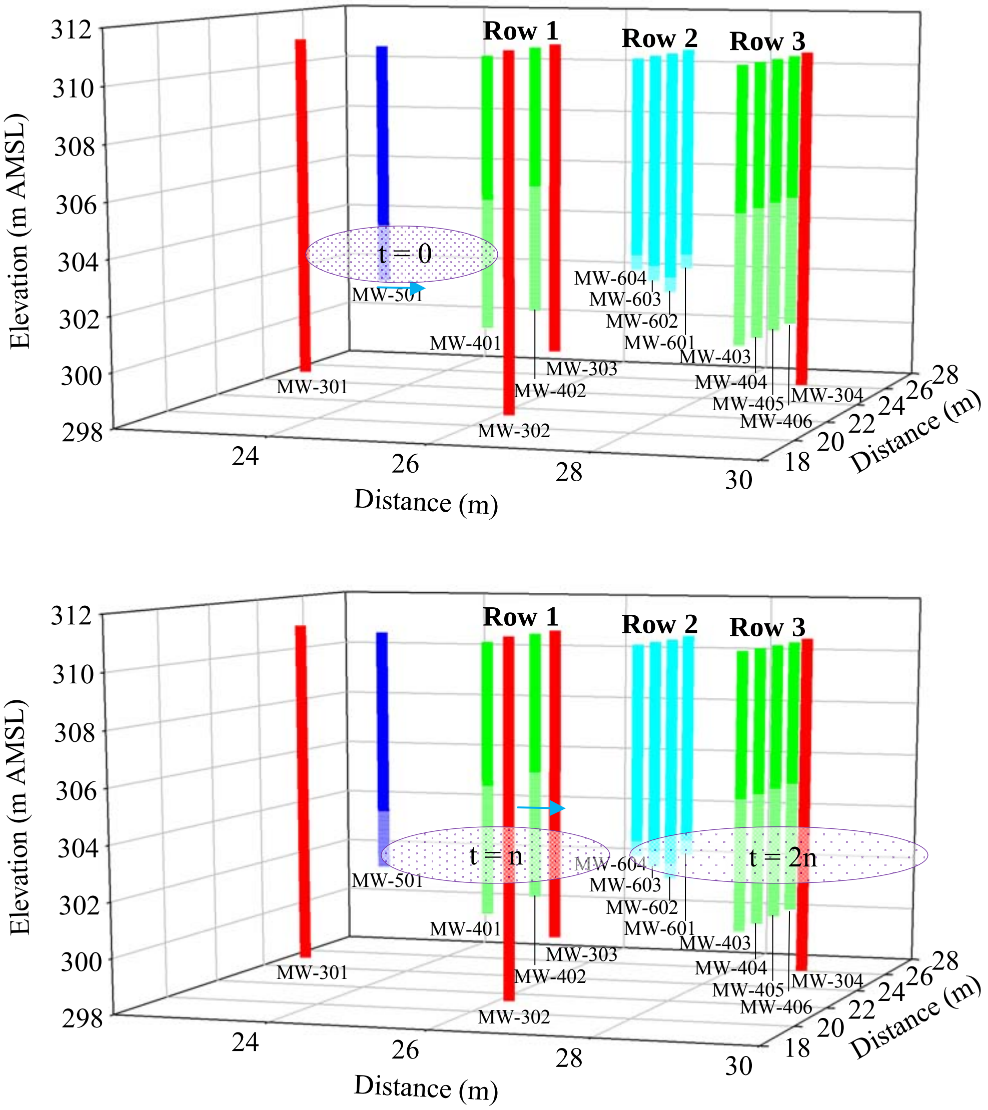

Figure 5.5: Cross-sectional view of the transport of the injected slug at t = 0 days, immediately following injection phase and after a period of time has passed; t = n and t = 2n, assuming homogeneous delivery into Unit 4. The injected slug was subject to aquifer dispersion, diffusion and dilution due to aquifer mixing processes.

5.6 Tracer Analysis of Remedial Test Solution

The objective of the experimental design was to evaluate the delivery and utilization of a remedial test solution to anoxic regions of a petroleum-contaminated source zone using NO_3^- as a TEA to enhance bioremediation. Temporal sampling of conservative tracer Br^-, reactant NO_3^- and degradation products including NO_2^- and NH_4^+ were measured to determine the successful delivery and microbial utilization of the injected test solution.

Breakthrough curves were plotted using relative concentrations (C/C_o) for each solute, where C is the measured concentration and C_o is the injected concentration. Bromide concentrations were measured in all of the 1475 groundwater samples collected, while NO_3^- and NO_2^- analysis was only conducted on 50 of those samples.

The total quantity of Br^- tracer recovered was determined by integrating the area under each breakthrough curve using the Mass Flux Calculation Method applied by Mocano (2005) and described by API Groundwater Remediation Strategies Tool (2003). The Mass Flux Calculation Method entails measuring the total tracer mass flux across a transect determined by the cross-sectional area of multilevel wells downgradient of injection well MW-501 in rows 1, 2 and 3 (Figure 5.6) at a certain moment in time as described in equation (5.3) below:

$$\mathrm{MF} = \sum_{i=1}^{i=n} q_i C_i A_i \qquad (5.3)$$

Tracer concentration C_i for each point in the transect was assigned to area A_i (dimensions half-way to the adjacent points), and Darcy Flux q_i, as discussed in section 2.6.2 in Chapter 2. Darcy flux is assumed to be constant over time, however, it was assumed to vary with the K for each aquifer unit that the sampling point was screened across; Unit 2 q = 0.17 m/day, Unit 3 q = 0.12 m/day and Unit 4 q = 0.05 m/day.

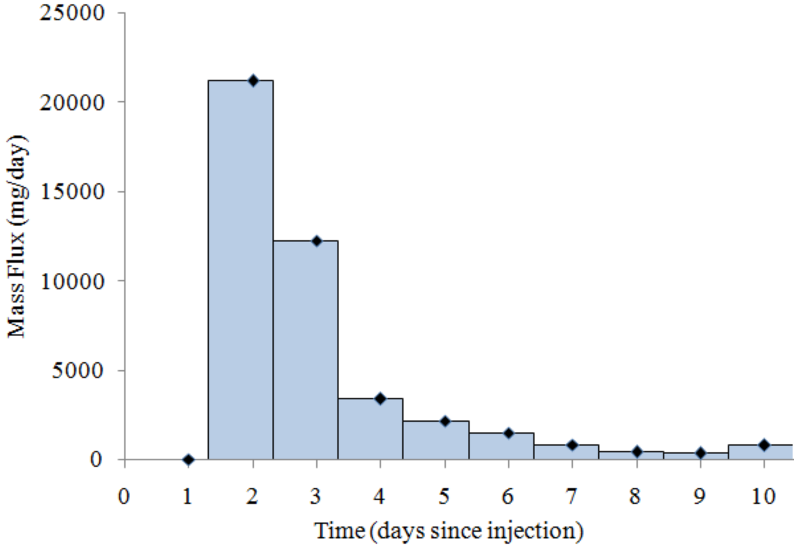

Figure 5.6: Mass Flux Calculation Method. Total mass of tracer intercepted in downgradient monitoring wells at a specific moment in time was determined by integrating the area underneath the breakthrough curve.

5.7 Treatment System Evaluation

5.7.1 Field Biodegradation Rates

The concentration of tracer, reactants and possible reaction products were measured to obtain breakthrough curves for all solutes of interest. Breakthrough curves for reactive solutes and products may be used to quantify microbial activities using first rate reactions (e.g. Haggerty et al, 1998; Istok et al., 1997). The quantification of Br^- tracer is used to account for physical processes, as groundwater velocity contributes to the displacement and dilution of the amended solutes through advection and dispersion, while concentration gradients contribute through molecular diffusion (e.g. Addy et al., 2002).

In situ biodegradation rates are likely variable in the field scale related to chemical and physical variations in the aquifer environment including the availability of electron acceptors, organic contaminants and nutrients (Allen-King et al., 1994). Previous studies have indicated that higher contaminant concentrations and anaerobic redox conditions (e.g. Cozzarelli et al., 1999) or lower microbial activity (e.g. Aelion, 1996) are present in lower hydraulic conductivity units in heterogeneous units of petroleum-contaminated sites. It is essential to identify lower permeable units containing residual contaminants as they will influence the remediation time periods. The variable permeability of the aquifer materials was previously addressed in Chapters 2 and 3, in relation to contaminant distributions. Aelion (1996) described biodegradation rates of toluene and benzene varying as a function of sediment type and levels of microbial activity, where fine grained clay materials had increased sorption and limited biodegradation.

Rates of denitrification are obtained by computing first-order rate constants for the utilization of NO_3^-. First-order reaction assumes that the reactant is transformed in the aquifer and is corrected for dilution effects according to equation (5.4):

$$\ln\left[\frac{C*_{NO_3^-}(t)}{C*_{Br^-}(t)}\right] = -kt \tag{5.4}$$

Where $C*_{NO3}$- is the relative concentration of the reactant, nitrate and $C*_{Br}^-$ is the relative concentration of the Br^- tracer, t is the time elapsed since the end of the injection and k is the first-order denitrification rate coefficient. A plot of ln ($C*_{NO3}$-/$C*_{Br}$-) versus t generates a straight line with a slope –k. Estimates of first-order rate coefficients for NO_3^- reduction were determined by fitting the slope and intercept of the equation to experimental breakthrough data. The first-order reaction analysis assumes that the injected test solution within the aquifer is well mixed and that the advection-dispersion-sorption transport properties of the tracer and reactant are similar (e.g. Haggerty et al, 1998; Schroth et al, 2001).

5.7.2 Post-Injection Residual Evaluation

Soil cores were retrieved from the experimental zone in October 2009 by another MSc. Earth Sciences Candidate, Bobby Katanchi, and analyzed for the critical aromatics BTEXTMB. The soil cores were collected in the zone of the aquifer where significant NAPL concentrations had been found, extending between 308 and 302 m AMSL (3 and 9 m bgs). The targeted residual zone of interest within the aquifer was 303 to 305 m AMSL (6.2 to 6.8 m bgs).

Groundwater samples collected from multilevel sampling points in the aquifer target area were analyzed for BTEXTMB and TPH. Groundwater quality measurements were not anticipated to differ from pre-treatment results, considering the dissolution of residual NAPL remaining would cause groundwater concentrations to rebound (e.g. Cunningham et al., 2001). The results of the tracer test experiment and evaluation of bioremediation via denitrification are discussed in further detail in Chapters 6 and Chapter 7, respectively.

Chapter 6: Remedial Tracer Test Br^- Results

6.1 Evaluation of the Delivery of Remedial Tracer Solution

The delivery of the remedial test solution below the water table targeted a select zone of the aquifer contaminated with residual petroleum hydrocarbons. The test solution was amended with conservative bromide (Br^-) and reactive nitrate (NO_3^-) tracers. Groundwater tracer utilization allowed for detection of contaminant transport pathways and the ultimate delivery of remedial solution to petroleum hydrocarbon impacted zones. This chapter discusses the delivery results of the remedial solution within target zones of the aquifer and the effect of natural transient hydrogeological conditions present at the Site.

6.2 Injection Effects on Hydrogeologic Flow Regime

The forced injection of a large volume (2.05 m^3) of remedial tracer test solution resulted in a localized water-table rise, noted in wells up to 3.7 m away. Water table mounding occurred as a result of the remedial solution displacing existing groundwater within the immediate vicinity of the injection interval. The hydrogeological changes were relatively short-lived, with the water level within the zone of influence recovering 80-100% within 90 minutes of the completion of the injection phase.

Water levels in MW-501 and neighbouring wells were monitored during the delivery of the test solution to establish hydrogeological characteristics of the aquifer materials in relation to the injected remedial slug below the water table. The observed water level changes throughout injection and recovery phases are presented for injection 12 (November 18th, 2010) in Figure 6.1. Observation wells were screened within the same aquifer formations as the injection well (primarily Unit 4), although portions of the delivery interval also penetrated the overlying sand and gravel, Unit 3. Water levels were monitored at MW-401 and MW-402, screened across the static water table and located in Unit 3 (MW-402 port 4) and Unit 4 (MW-401 port 4), consistent with the injection interval. MW-603 is screened at greater depth (7.43-7.93 m AMSL) across Unit 4 (sand) and Unit 5 (sand and gravel, till) as described in Appendix A.

Groundwater mounding in the aquifer adjacent to MW-501 was estimated to be as great as 1.95 m during the injection phase. This inference is based on the Thiem-Jacob method or inverse distance-drawdown approach; determined using water level data from observation points measured at various distances downgradient from the well as described in Appendix E. The maximum change in hydraulic head measured in MW-501 was 6.82 m during the injection phase. Due to natural fluctuations in the centrifugal pump, it was often necessary to make small adjustments to the pump rate to prevent overflowing water levels in the injection well, as indicated in Figure 6.1 at time, t = 6, 33 and 44 minutes. Fewer pump adjustments were required during water level monitoring within the injection well during periods of high groundwater levels, compared to low levels which were apparent in the fall and applicable during Injection No. 12. This change is attributed to the reduced transmissivity of the receiving formation; i.e. reduced aquifer thickness and the unsaturated zone being less permeable.

Groundwater levels in MW-402-4 located 2.4 m downgradient of MW-501, increased by 0.48 m compared to a rise of 0.13 m observed in MW-603 situated 3.7 m away screened within the bottom of Unit 4. No water level changes were observed in MW-405-3, fully screened in Unit 4 and located 6.4 m downgradient of MW-501, evidently beyond the radius of influence of the injection. Groundwater levels in the injection well and neighbouring observation wells gradually declined upon completion of the injection phase (at t = 66 min in Figure 6.1).

The interim groundwater rise generated during the injection resulted in a temporary increase in the horizontal hydraulic gradient (Fig. 6.1) and the subsequent groundwater transport was increased up to 12 times of the pre-injection groundwater velocity between MW-501 and Row 2. The interim change in hydraulic conditions present across the study area resulted in a short-term increase of groundwater flow and subsequent transport of the remedial slug within the treatment zone. Groundwater mounding also resulted in changes in saturated conditions, where the remedial solution was incorporated into previously unsaturated materials during seasonal low groundwater levels.

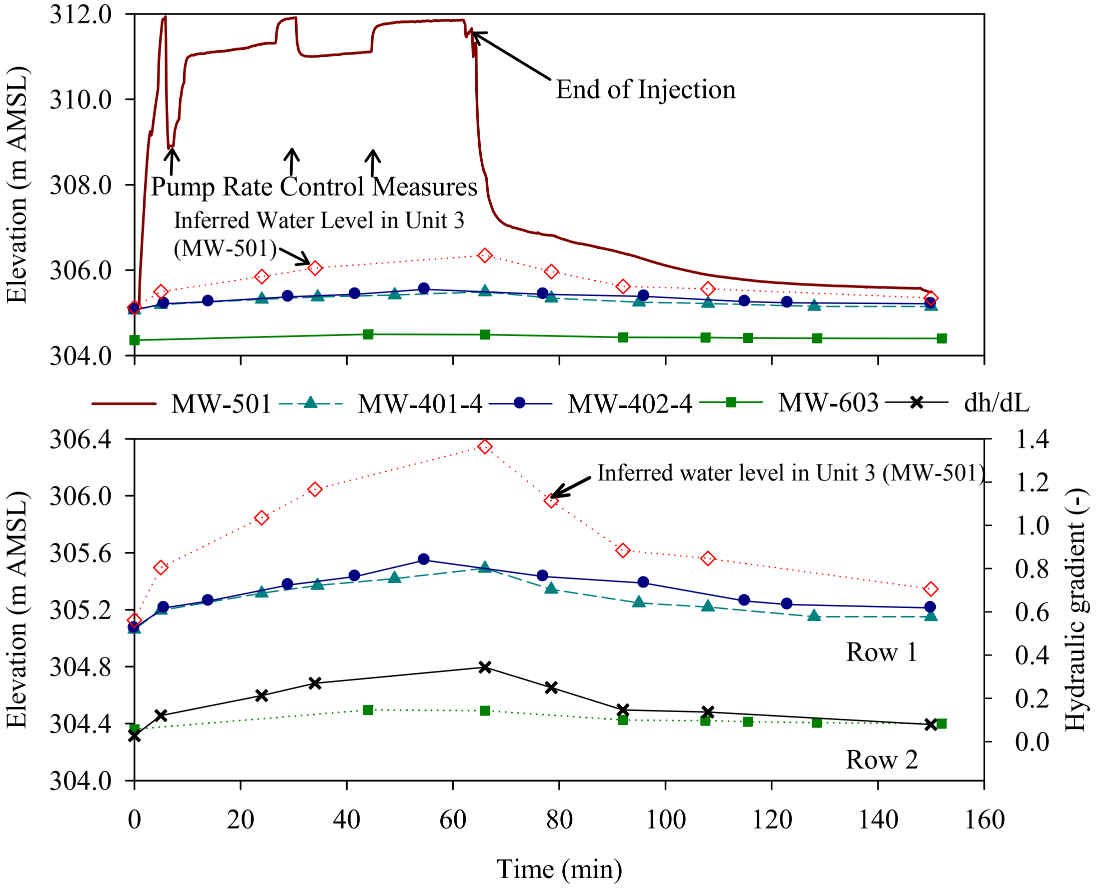

Figure 6.1: Horizontal hydraulic gradient and groundwater level changes observed at injection well MW-501, Unit 3, inferred by the Thiem-Jacob method, and downgradient monitoring wells located in Row 1 (MW-401, MW-402) and Row 2 (MW-603) during and post-injection of remedial solution below the water table.

6.3 Subsurface Behaviour of the Remedial Tracer Test Solution

6.3.1 Injection Well MW-501

The objective of the injection schedule was to create a plume of remedial solution in a select zone of the residual petroleum hydrocarbon contaminated anaerobic aquifer. This would provide a continuous supply of terminal electron acceptor to the indigenous microbial community, enhancing the biodegradation of contaminants of interest in the groundwater system. The transient nature of the local groundwater flow system greatly influenced the removal of the remedial slug within MW-501 within the duration of the 12 injections. Groundwater levels declined approximately 1.45 m at a relatively constant rate over the 121 day period the tracer tests were conducted. The remedial solution was consistently delivered below the water table; although the groundwater level dropped beneath the top of the sand pack in Unit 3, to approximately 0.15 m above the screened interval of MW-501 within Unit 4 during Injection 11 and Injection 12.

The remedial pulse delivered to the subsurface environment mixed and dispersed within the background contaminated groundwater. In general, normalized Br^- tracer concentrations (C/C_o) remained approximately 1.0 in MW-501 for at least an hour following the injection prior to being dispersed by the local hydrogeological flow regime. The transport of the injected remedial slug from the injection well is generally described by three unique type behaviour breakthrough curves (BTC) observed throughout the 12 injections performed over the 121 day period. Representative Type I, Type II and Type III BTCs, obtained from Br^- tracer monitoring of MW-501, are presented in Figure 6.2. Transient groundwater flow conditions drove the dilution and rate of removal of Br^- tracer in MW-501.

Breakthrough curves (BTC) are classified as Type I for injections 1-6, occurring between July 28 and August 17, 2009 and are illustrated in Figure 6.2a. The BTC for the initial injection possesses a longer elution tail compared to the other injections also classified as Type I. This may be attributed to the limited initial well development, as the hydrogeological conditions only differed slightly over the course of the 6 injections. Due to the rapid disappearance of Br^- in MW-501 (at times less than 2 days), it was not possible to satisfy the conditions where a subsequent injection would be initiated at the target concentration, when $C/C_o \approx 0.5$.

Type II Br^- tracer BTCs (Fig. 6.2b) depict the removal of Br^- from the injection well for injections 7 and 8 which took place on August 25 and September 9, 2010, respectively. Relative tracer concentrations reached the target concentration within 4 days of the injection. Groundwater levels had reduced by approximately 0.85 m since injection 1 and a decrease in hydraulic gradient from 0.007 to 0.004 was observed across the Site.

BTCs for injections 9-12, between September 24 and November 18, 2009 are classified as Type III cases (Fig. 6.2c). Both groundwater levels and hydraulic gradients, i, were at a seasonal low during the Type III case ($i < 0.004$), resulting in limitations to the transport of remedial solution within the saturated zone. Normalized Br^- tracer concentrations were indeed greater than the injection criteria 24 to 121 days following an injection, indicating an increase in the residence time of the injected slug. The pulse of remedial solution delivered to the groundwater flow system was generally subject to less advective compared to dispersive dilution processes under the reduced hydrogeological conditions encountered in the fall. Under these conditions, increased tailing of $C/C_o > 0.5$ was observed as great as 121 days post-injection.

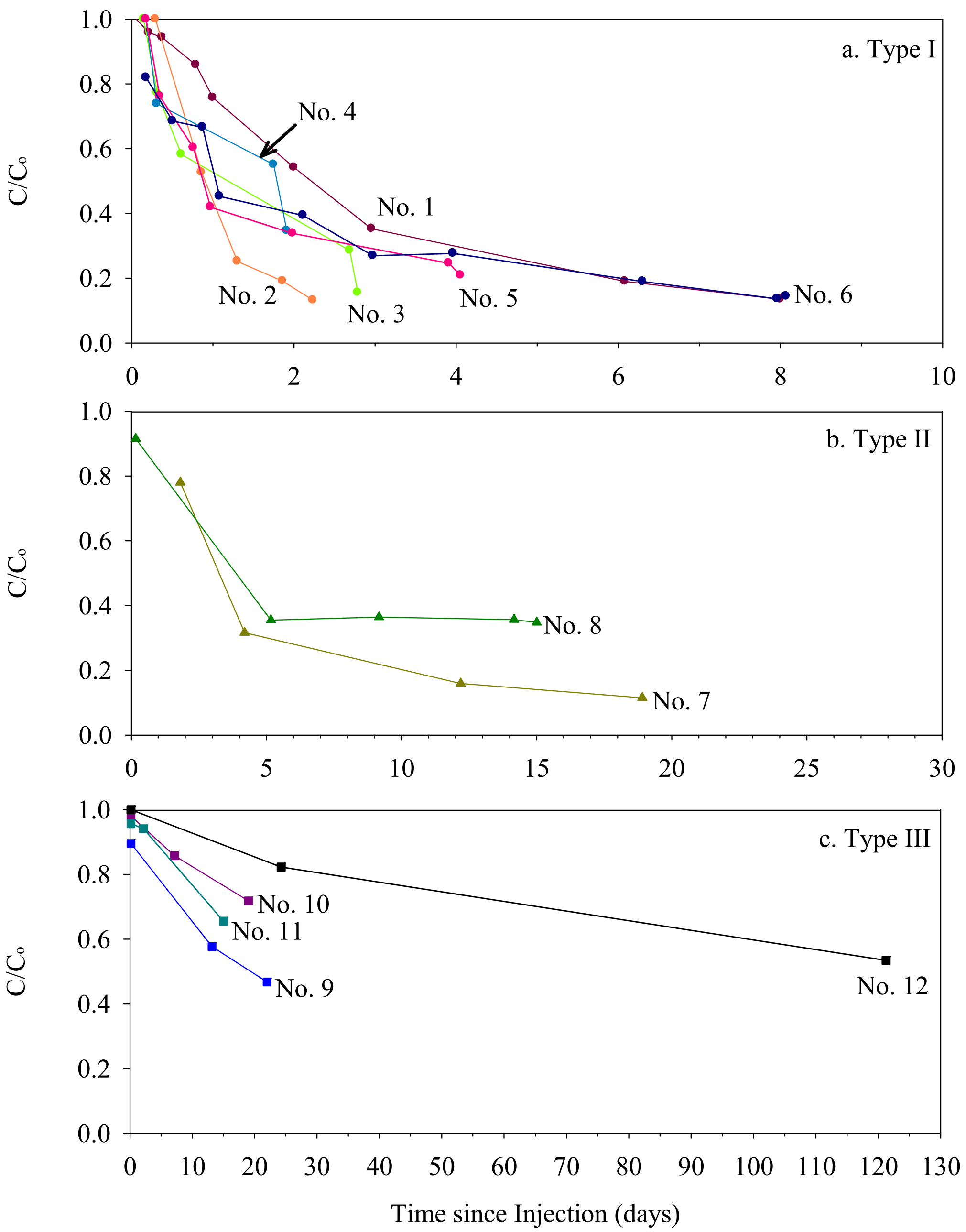

Figure 6.2: Type I (top) rapid removal of Br^- tracer in MW-501 under high water table conditions driven by high horizontal gradient. Type II (middle) increase in time required for C/C_o to reach target value. Type III (bottom) significant increase in time required for tracer to be removed to $C/C_o = 0.5$.

6.3.2 Delivery of Remedial Tracer Solution within the Monitoring Network

The following assumptions were made in interpreting the delivery of remedial test solution (injectate) amended with reactive NO_3^- tracer into the aquifer:

1) No significant density contrast exists between the injectate and background groundwater;
2) Remedial pulse (slug) was introduced instantaneously into the uniform flow field;
3) Tracer solution flowed radially outward into the aquifer and was homogeneously distributed.

Density effects have been observed with Br^- tracer concentrations of 324 mg/L (Freyberg, 1986) and 700 mg/L (Oostrom et al., 1992), however no Br^- (detection limit of approximately 2 mg/L) was found at depths greater than the injection zone when the remedial solution was amended with 200 mg/L Br-.The remedial solution was introduced into the subsurface environment within approximately 60 minutes, at an average rate of 35 L/min. Due to the short duration of the injection interval, a pulse injection is presumed.

Assuming the remedial solution flowed radially outward from the injection interval and was homogeneously distributed, the radius of the injectate delivered into the aquifer can be described by equation (6.1), below:

$$ROI = \sqrt{\frac{\frac{V_i}{L\pi}}{n}} \tag{6.1}$$

Where *V* is the volume of remedial solution injected into the aquifer (2.05 m^3), L is the vertical delivery length (3.2 m) and *n* is the porosity of the aquifer materials, 0.32.

By applying equation (6.1), the radius of the remedial test solution injectate was estimated to be 1.4 m with an equivalent diameter of 2.8 m. The observed width of the injected remedial solution ranged from less than 1 m to approximately 3.5 m in the direction of groundwater flow. The dispersal of the tracer within the monitoring network was inferred by triangulation of the maximum C/C_o observed for the shallowest sampling ports of the following eleven observation points: MW-301, MW-302, MW-303,

MW-304, MW-401, MW-402, MW-403, MW-404, MW-405, MW-406 and MW-501 as illustrated in Figures 6.3 and 6.4. Concentrations of Br^- at the sole upgradient multilevel well, MW-301 (situated approximately 1 m upgradient of the injection well) were non-detectable.

Results of the groundwater sampling program conducted 1 hour following the injection phase suggest the injected slug took on a narrow and elongated shape in the subsurface under seasonally high groundwater transport conditions (July-August 2009) as illustrated in Figure 6.3. At this time the slug was primarily transported directly west of injection well by advection and intercepted by MW-302.

The radius of influence of the injected slug increased during consecutive injections, influenced by the displacement of amended water from the previously injected test solution. The remedial cloud tended to flow primarily towards the west-northwest, perhaps with a wider spatial distribution, during the final remedial injection on November 18, 2009 (Fig. 6.4). Peak concentrations of Br^- tracer were encountered at MW-302 and MW-401, situated approximately 1.2 m apart compared to Injection 1. Under reduced groundwater flow conditions occurring at the end of August and continuing into the fall (September to November), dispersive processes may have played a more significant role contributing to the horizontal distribution of remedial test solution in the subsurface. Dispersion causes the tracer to spread out over an area that is larger than it would be expected to occupy due to advection alone from radial flow paths in the saturated environment (Bear, 1972).

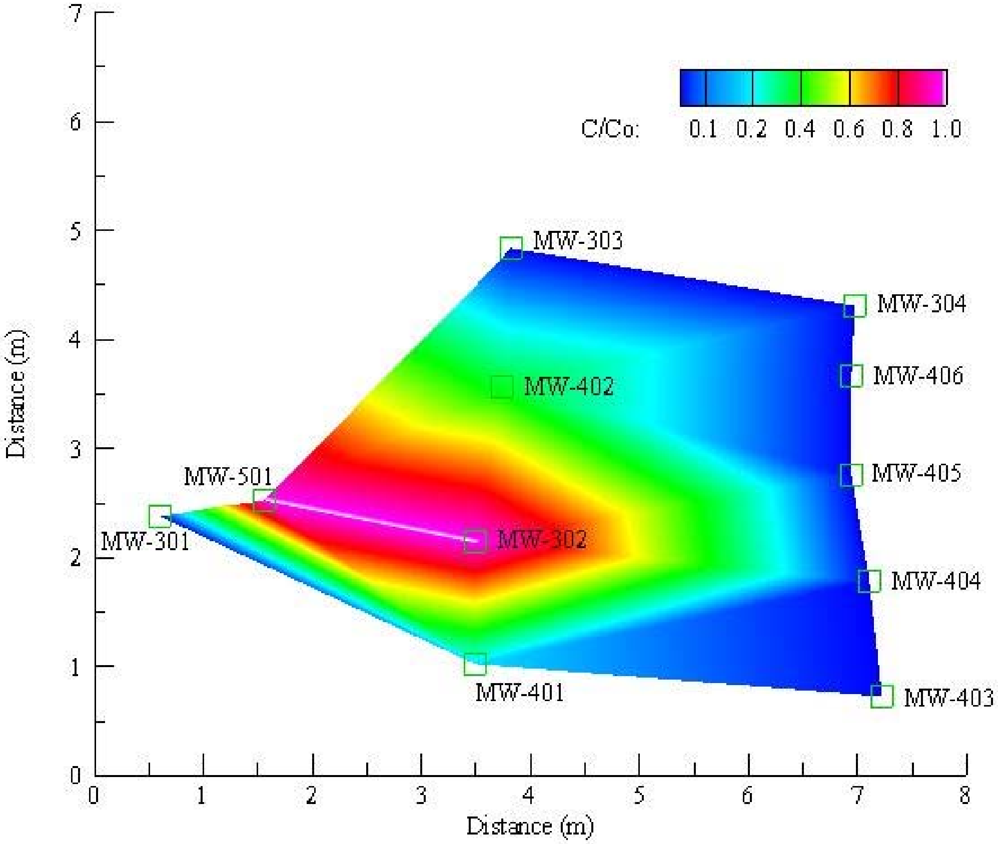

Figure 6.3: Plan view of the horizontal distribution of remedial solution slug in sand and gravel Unit 3, approximately 1 hour following the injection 2 conducted August 5, 2009. Boxes denote groundwater sampling locations.

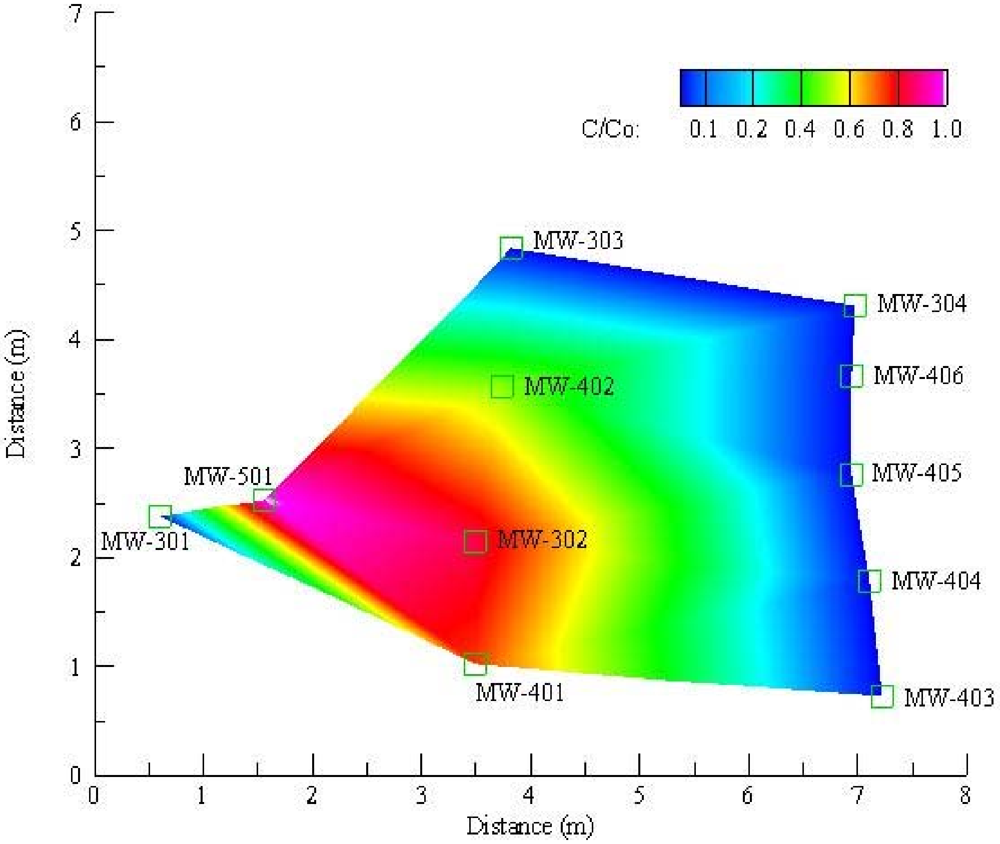

Figure 6.4: Plan view distribution of remedial solution slug in Unit 4, approximately 1 hour following the injection 12. Boxes denote groundwater sampling locations.

The remedial slug was assumed to flow radially from the injection interval, however the shape of the injected slug within the subsurface was subject to aquifer heterogeneities, the initial saturated thickness delivery interval, the injection rate and duration, in addition to well construction and development methods (Istok et al, 1997).

The radius of influence (ROI) within the injection interval is primarily influenced by the hydraulic conductivity (K) of the heterogeneous aquifer materials (Fig. 6.5). The injection well is screened across a 2 m interval of Unit 4 ($K_4 = 3.1 \times 10^{-5}$ m/s), with the sand pack extending 1.2 m above into a slightly more permeable Unit 3 ($K_3 = 6.9 \times 10^{-5}$ m/s). Under high saturated conditions encountered during the early injections, remedial solution delivered to Unit 3 had a greater radius of influence compared to Unit 4 due to the larger associated K value and aquifer thickness resulting in a higher ability to transmit remedial solution.

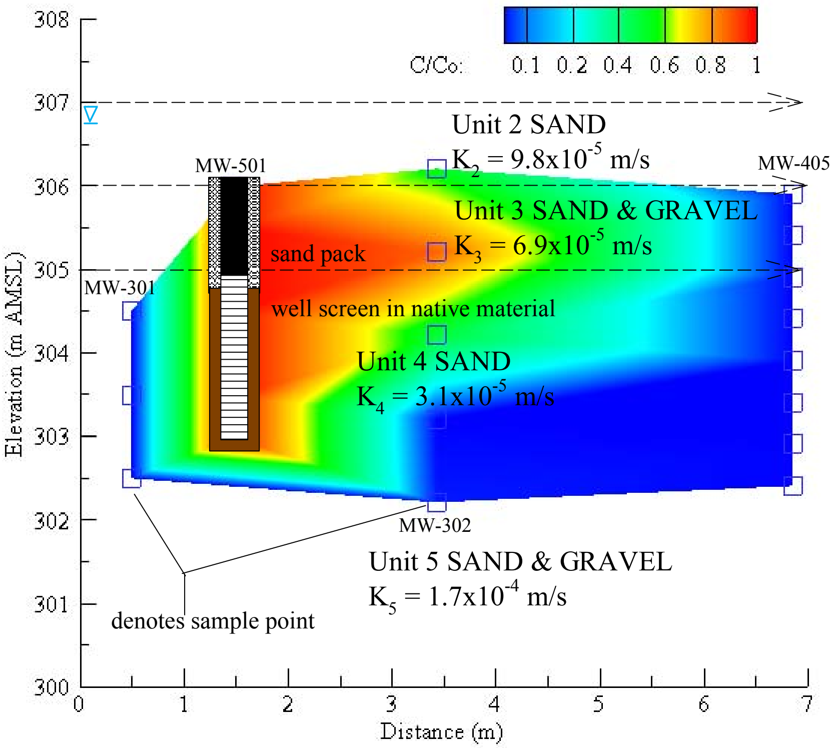

Figure 6.5: Cross-sectional view of remedial tracer distribution in the subsurface at 1 hour following Injection 1, July 28, 2009 under seasonal high hydrogeologic conditions Water table located at 306.78 m AMSL. Sampling locations denoted by boxes along cross-section.

Different radial flow pathways were established under the reduced saturated conditions. Cross-sectional views of the tracer distribution within the subsurface at time, t = 1 hour following the injection, as shown in Figure 6.6, indicate the remedial pulse primarily delivered to the bottom of Unit 4 under lower water table conditions. Early arrival of peak tracer concentrations within the lower portion of Unit 4 is attributable to more conductive sandy aquifer materials at the base of Unit 4.

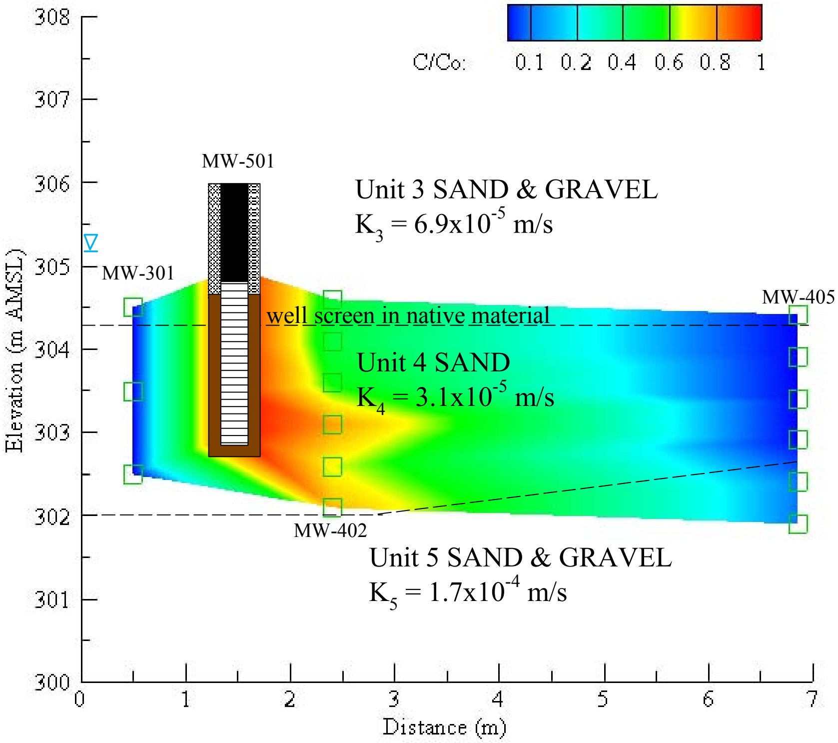

Figure 6.6: Cross-sectional view (MW-301, MW-501, MW-402 and MW-405) of remedial tracer distribution in the subsurface following Injection 12, November 18, 2010 under seasonal low hydrogeologic conditions. Water table located at 305.14 m AMSL, ports 1, 2 and 3 of MW-402 and MW-405 were dry.

6.3.3 Temporal Distribution of Injectate at Downgradient Monitors

BTCs were generated for select monitoring wells and are organized by the stratigraphic unit screened; Unit 2 (sand), Unit 3 (sand + gravel till), Unit 4 (sand) and Unit 5 (sand + gravel till). The well description and location of each groundwater monitor is presented in Appendix 2.

Br^- tracer behaviour in Unit 2 (0.5 m average thickness across study area) was monitored by sampling groundwater at MW-302-5, screened 306.3 and 306.1 m AMSL (4.8-6.0 m bgs) and directly above the interval of injection (306 to 302.8 m AMSL). Peak relative concentration of Br^- recovered in Unit 2 ranged between 0.6 and 1.0 for injections 1 through 6 (Fig. 6.7).

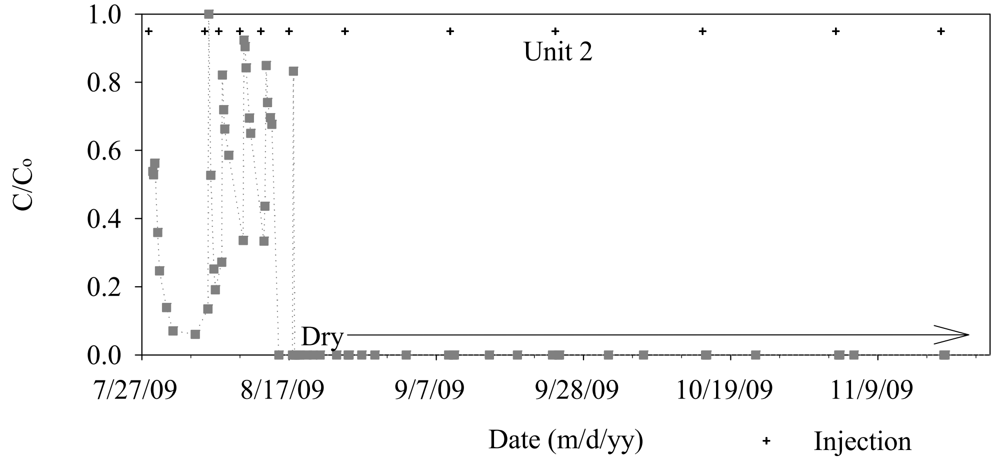

Figure 6.7: BTC for injections 1-12 in MW-302 port 5 screened in Unit 2 for Injections 1-12. The groundwater level in the vicinity of sampling point declined below 306.33 m AMSL, which subsequently led to the sample point being dry for injections 6 – 10.

Br^- arrival in Unit 2 was interpreted to be the result of flow from the highly conductive sand pack material (No. 1 sand, estimated $K = 1x10^{-4}$ m/s using Hazen solution). The groundwater monitor was situated in the upper portion of the saturated zone during the early injections. It was not possible to collect a groundwater sample in Unit 2 for injections 6 onwards, as the water table dropped below sampling point MW-302-5. The results of the BTCs in Unit 2 (Fig. 6.7) reveal that background C/C_o concentrations increased steadily with each injection, as a result of the continuous level of remedial solution delivered to the subsurface. The arrival of tracer in Unit 2 corresponding to each individual injection is presented in Appendix E.

Br^- tracer behaviour in Units 3, 4 and 5 was monitored at multilevel wells MW-302, MW-401 and MW-402 located in Row 1, approximately 2-2.4 m downgradient of injection well MW-501. Peak relative concentrations of Br^- observed in each formation was influenced by several factors, including the proximity of the sampling point (shortest distance travelled), permeability of the unit screened and the alignment with the groundwater flow path. The results of the arrival of the remedial test solution in each unit, at the first fence of multilevel wells downgradient of injection well MW-501, are presented in Figure 6.8.

The highest relative concentrations of Br^- tracer within formations 3, 4 and 5 occurred repeatedly in MW-302, situated nearest to the injection well and within the direct path of groundwater flow, as illustrated in Figure 6.8. Multilevel wells MW-401 and MW-402 were each located the equivalent distance away from the injection well; however, groundwater flow direction was inferred to be slightly towards the west-southwest for most of the injections and primarily intercepted by MW-402.

There was no evidence of important preferential subsurface flow found in the measured Br^- breakthrough curves within each respective aquifer unit comprised of similar aquifer materials (Fig. 6.8), however the evaluation of BTCs gave indication of fast preferential flow paths between units 2, 3, 4 and 5 (Fig. 6.7 and 6.8) based on peak concentration arrival times. Later injections in October and November reveal that MW-401 had C/C_o breakthrough values similar to MW-402 in Unit 3(Injection No. 8, onwards) and Unit 4 (Injection 12 only), possibly resulting from seasonal changes in groundwater flow patterns. Peak concentrations of Br^-, measured in Units 3 and 4, occur immediately following an injection, however, there is an apparent delay in tracer arrival in Unit 5 within injections 1-9, where a maximum C/C_o value was not measured until post-injection 4. In general, the peaks of the BTCs and elution trails broadened over time due to effects of dispersion which increased as transport velocities decreased due to seasonal effects.

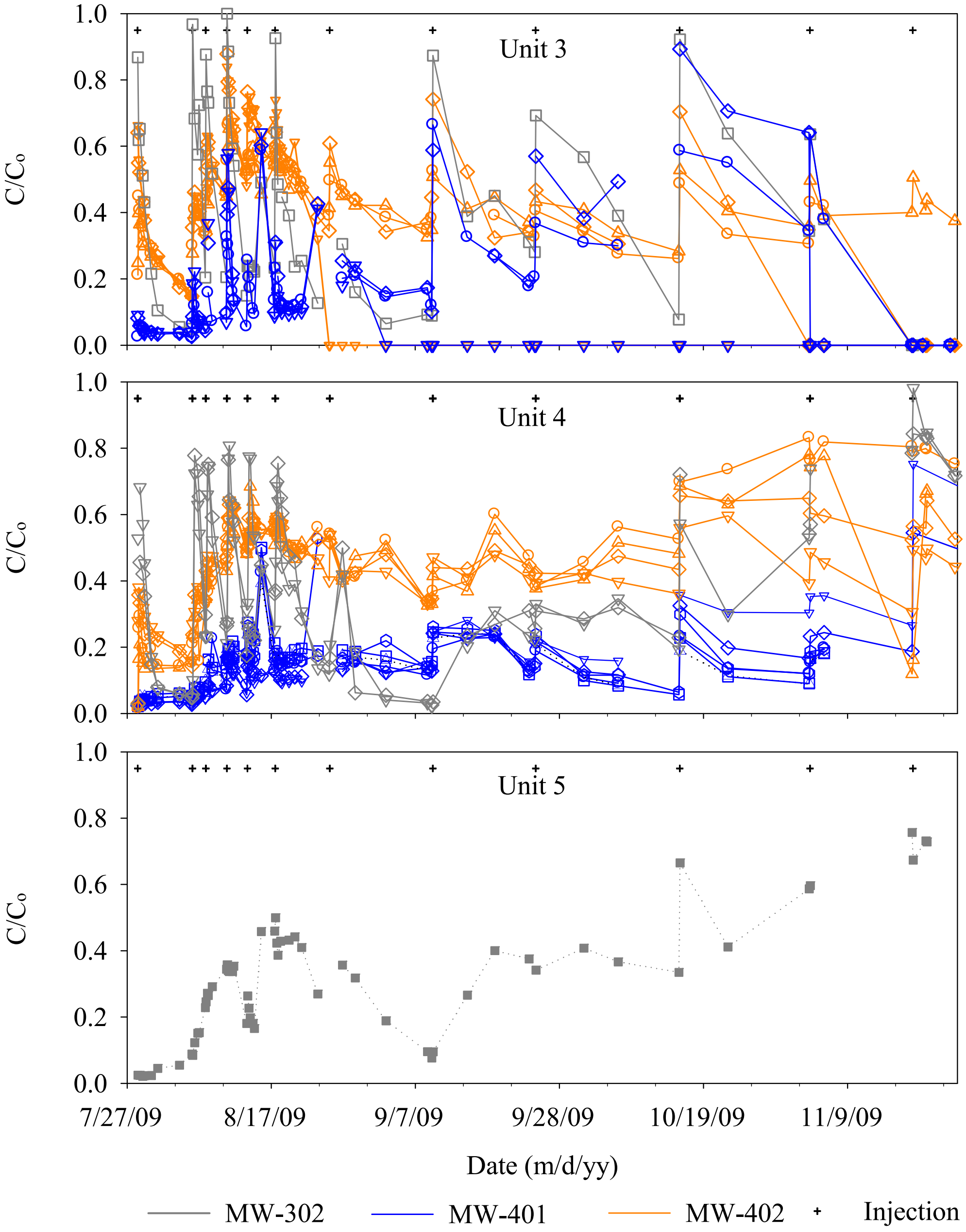

Figure 6.8: BTC for injections 1-12 in Unit 3 (top) for MW-302 (6), MW-401 (1, 2 & 3) and MW-402 (1, 2, 3 & 4); Unit 4 (middle) for MW-302 (7,8), MW-401 (4,5,6,7,8,9) and MW-402 (5,6,7,8,9); and MW-302 (9). Multilevel sampling points in Unit 3, MW-302 (6), MW-401 (1,2,3) and MW-402 (1,2,3) became irrelevant (dry) gradually during the seasonal decline in water levels.

Background Br^- tracer C/C_o within the multilevel network at row 1 was consistently greater in MW-402, when compared to MW-302 and MW-401. The concentration of Br^- increased progressively with each pulse introduced due to the accumulation of mass solutes (Br^-) in the groundwater following consecutive injections. Throughout each consecutive injection, the most recent injected slug displaced pre-existing amended groundwater, resulting in a wider distribution of the remedial cloud in the subsurface as time progressed, however dispersive mixing was relatively minor given the short injection time. The average background C/C_o between injections in MW-402 Unit 3 and 4 was approximately 0.4, whereas the maximum average background C/C_o of 0.3 was calculated for MW-302 Unit 5. A complete summary of tracer conditions in specific aquifer formations of Row 1, immediately prior to each injection, is presented in Appendix E. The importance of the distribution of tracer between injections involves the delivery of remedial solution to target zones containing residual petroleum hydrocarbons and the duration of exposure, discussed in detail in subsequent sections of this chapter.

A fence of groundwater wells was installed in October 2009, parallel to the existing multilevel monitoring network, as part of B. Katanchi's research project (Katanchi, 2011) and referred to as Row 2, as previously discussed in Chapter 5. The wells, utilized to monitor the presence of the remedial plume between Row 1 and 3, were applicable to the monitoring program post-injection 10. A maximum relative concentration 0.1 of Br^- tracer was observed in MW-603, situated in Row 2 and approximately 3.7 m downgradient of the injection well in November 2009, however concentrations declined over time. A cross-sectional view of the horizontal distribution of the Br^- tracer/ remedial plume along the groundwater flow path is presented in Figure 6. 9 illustrating the decrease in Br^- tracer concentrations with increasing distance from the injection well related to dispersive processes.

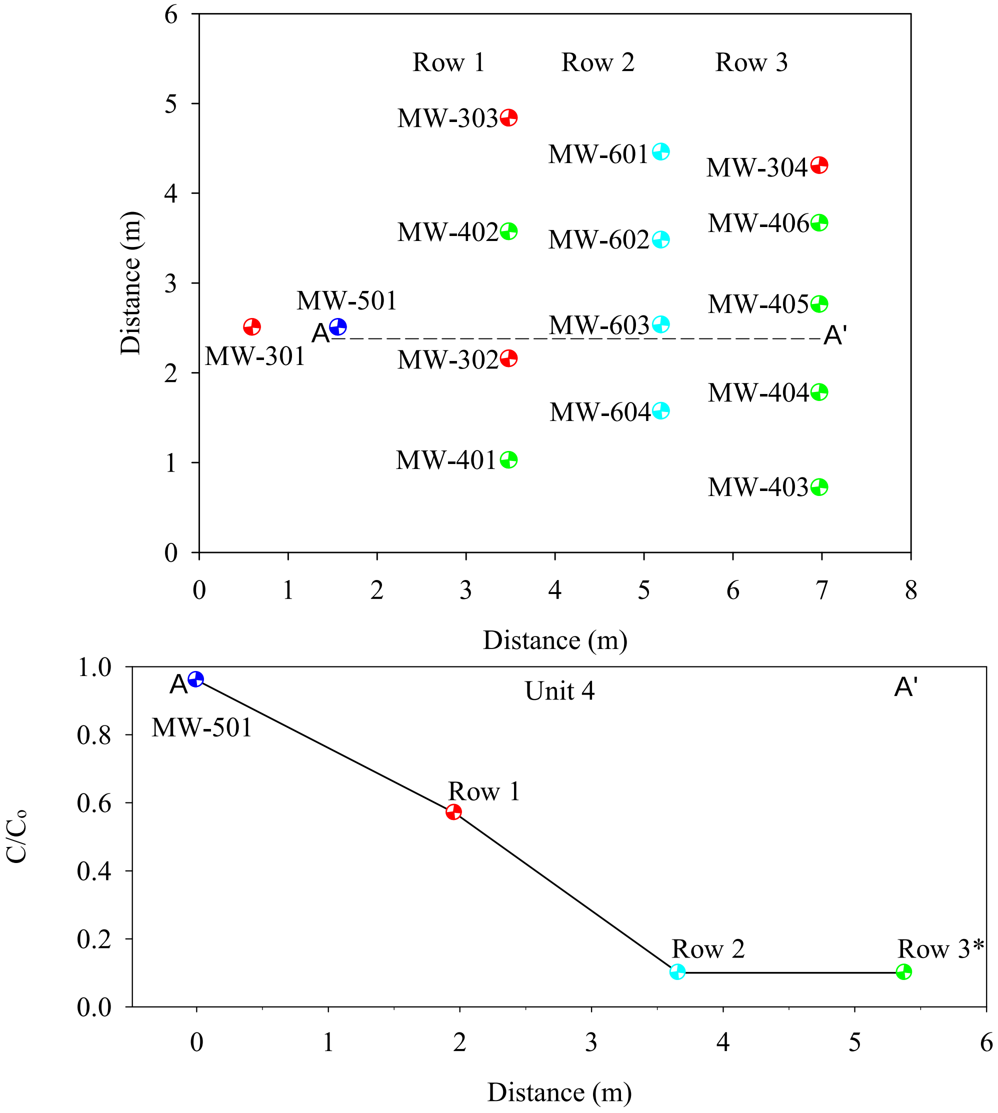

Figure 6.9: Cross-sectional view A-A′ of Br- tracer distribution in sandy aquifer Unit 4, within the downgradient monitoring network following Injection 11 on November 3, 2009. Data points correspond to MW-501, MW-302-8 (Row 1), MW-603 (Row 2) and MW-405-8 (Row 3, sand and gravel Unit 5).

Observation points correspond to C/C_o in Unit 4 aquifer materials screened between 306-303.20 m AMSL (MW-501), 304.33-304.13 m AMSL (Row 1), 303.52-303.02 m AMSL (Row 2) and 302.41-301.91 (Row 3), where Br^- was detected only in Unit 5 of Row 3. Despite the rapid arrival of remedial solution at Row 1 within the course of the injection (Figures 6.7 and 6.8), Br^- concentrations in MW-603 remained constant ($C/C_o = 0.1$).suggesting no significant presence of remedial solution in this segment of the aquifer.

Br^- arrival in Row 3 (Fig. 6.10) was limited to MW-405, port 8 screened in Unit 5 between 302.4 – 301.9 m AMSL (8.5 and 9 m bgs). The maximum observed length of the remedial solution plume within the study area was approximately 6.5 m after 62 days. Poor Br^- recovery at row 3 is likely attributed to dispersion dilution effects or the possibility that the migration of the injected slug followed different flow paths that do not intersect the test wells.

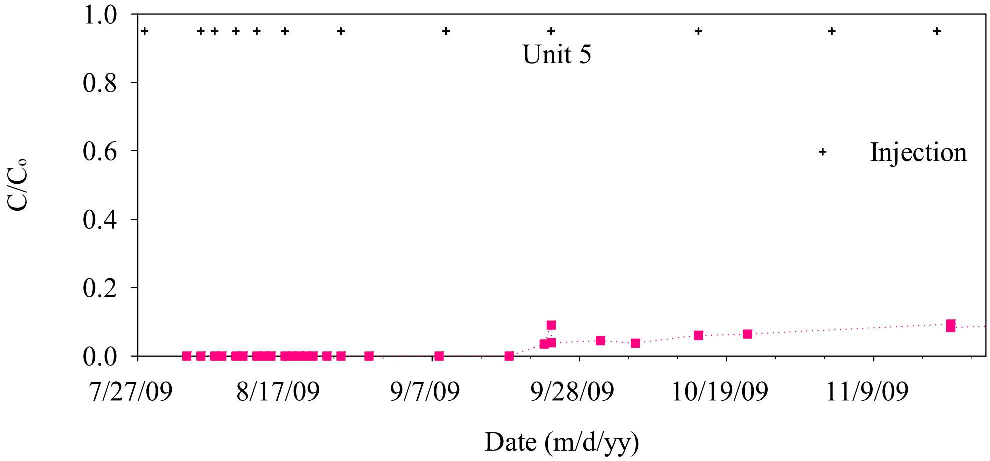

Figure 6.10: Breakthrough curve for MW-405 Unit 5, port 8.

Peak arrival of Br^- tracer at MW-405-9 was measured on September 24, 2009, approximately 63 days following the first injection on July 28, 2009, where concentrations of Br^- as great as 23 mg/L ($C/C_o = 0.1$) were observed. Br^- tracer concentrations at the monitoring point declined sharply, and then increased steadily to a second peak concentration measured November 20, 2009 (121 days). The first and second peak concentrations may be representative of the arrival of the centre of mass of the remedial slug delivered during injections 1 and 2. However, due to the limited data and low peak arrival concentrations, there is not enough evidence to conclude the exact travel times of each individual slug introduced into the subsurface. The gradual increase in Br^- tracer between September 24 and November 20, 2009 is however indicative that a continuous plume of conservative and reactive tracer amended test solution has reached the extent of the monitoring network, with an approximate 6.4 m length (Fig. 6.9).

6.3.4 Delivery of Remedial Solution in Heterogeneous Layers

Mass transport in heterogeneous formations is driven by highly conductive zones and their spatial connectivity (Mikovari et al., 1995). A comparison in Br^- tracer recovery between a high K (MW-402 Port 1, Unit 3, $K_1 = 5x10^{-5}$ m/s) and moderately permeable aquifer materials (MW-402 Port 7, Unit 4, $K_7 = 2x10^{-7}$ m/s) is illustrated in Figure 6.11.

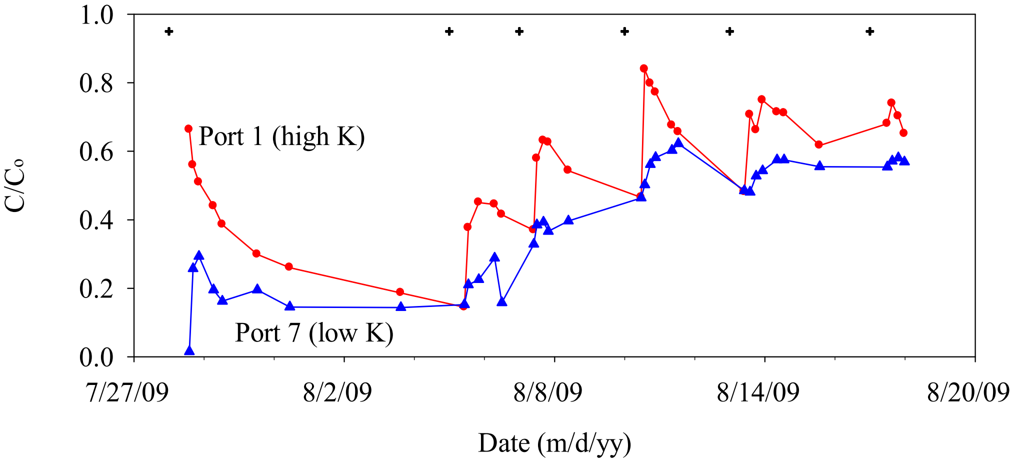

Figure 6.11: MW-402 breakthrough tracer curves for MW-402-1 and MW-402-7.

Elevated peak concentrations were consistently observed at MW-402 Port 1; however the remedial solution was also successfully delivered to less permeable materials at MW-402 Port 7. A general increase in peak concentrations and background C/C_o exceeding 0.5 between injections was eventually observed at both monitoring locations by injection 4. In each scenario, Br^- tracer breakthrough was subject to increased tailing with each subsequent injection. The repeated injections likely enhanced the mass of transfer of tracer solutes into the lower permeable zones.

Figure 6.12 depicts the vertical profile of Br^- tracer delivered to sand and gravel Unit 3 and sandy Unit 4, with hydraulic conductivity values displayed during the initial (6.12a No. 1) and mid-series (6.12 No. 7) and late stage injections (6.12c No. 11). The vertical profiles of the delivered tracer solution to

Unit 3 and Unit 4 is consistent with what was previously seen in Figure 6.8 immediately following the injection. For injection 1, Br^- had dropped to $C/C_o = 0.2$, while for later injections, the tracer remained near or above 0.4 after 8 days. This indicates that a continuous supply of remedial chemical was delivered to the subsurface, with higher concentrations being achieved during later injections when the ambient groundwater velocity was lower. The spatial variation in K inferred from grain-size analysis was often poorly correlated with the breakthrough data, especially under higher flow conditions apparent during injections 1 through 7. The Br^- breakthrough profile for Injection 11 is in better agreement with the vertical distribution of K values, most likely the result of the low gradient present across the Site at the time of the injection.

Under elevated groundwater levels (July – August, injection 1-6), early-time arrival of Br^- tracer (t=1 hour post-injection) occurred in the high permeability layers of Unit 2 and 3 and the upper zone of Unit 4. Reduced water levels (November, injections 11 and 12) led to remedial solution also being delivered quickly to deeper regions (Unit 4) (Fig. 6.12c). During seasonal high groundwater levels, the test solution flowed preferentially through the lower permeable zones of Unit 3 (Fig. 6.12a: MW-402, ports 1, 2, 3 & 4). The high permeable zone located in the lower portion of Unit 4 (Figure 6.12c: MW-402, ports 7, 8 & 9) was able to transmit the test solution more effectively under low seasonal groundwater levels.

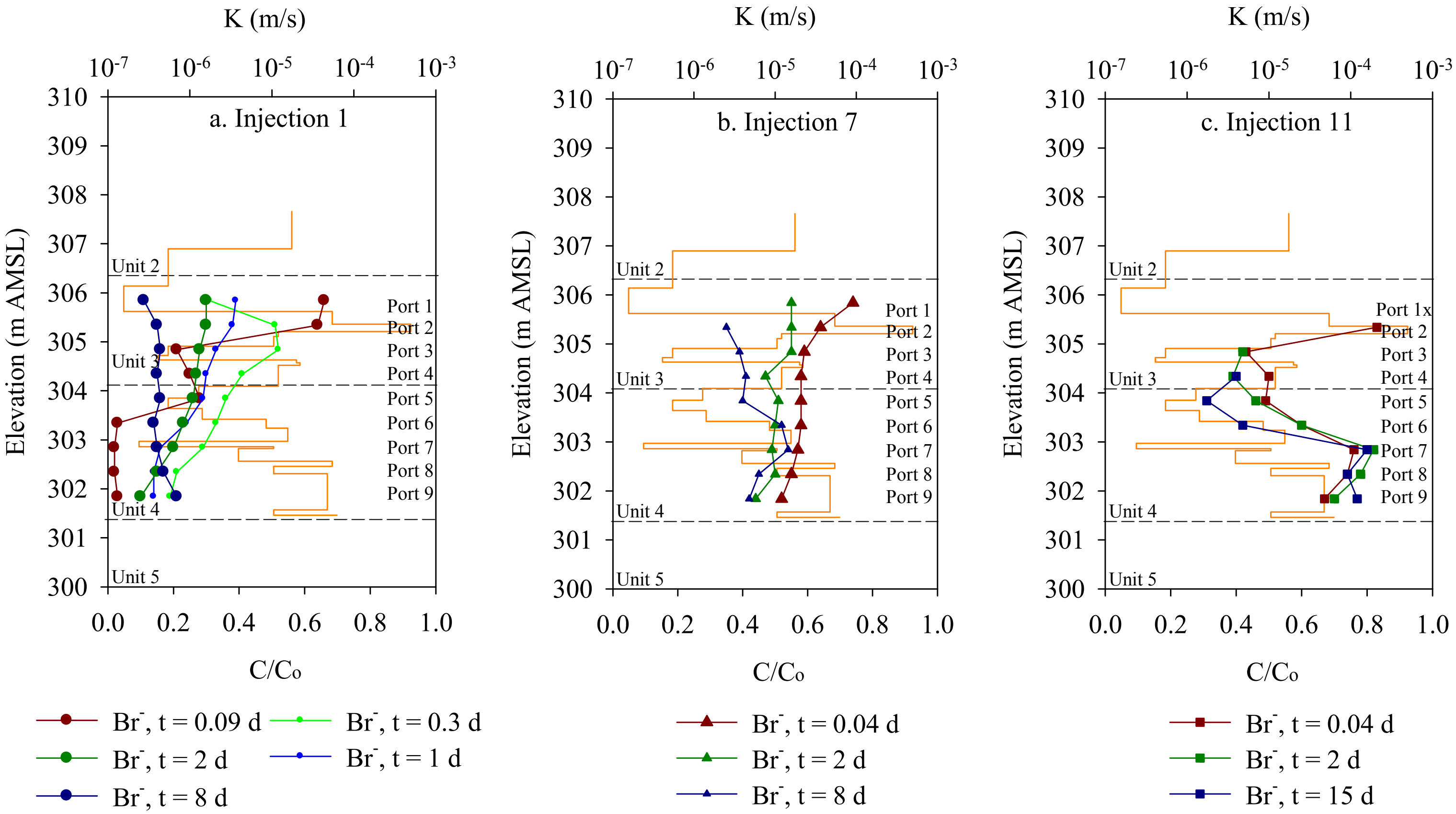

Figure 6.12: Normalized Br^- tracer time dependent vertical distribution at MW-402 corresponding to multilevel ports 1- 9 situated in Unit 3 and Unit 4 during Injection 1 (a), 7 (b) and 11 (c). Remedial test solution was delivered from MW-501 between 306 to 302.8 m AMSL. Time – t, corresponds to the number of days that have passed since the injection took place, where orange line denotes hydraulic conductivity (K) profile.

6.4 Transportation of the Remedial Test Solution

Characterization of aquifer parameters and groundwater velocity are important in determining the main transport processes in the aquifer. The fate and behaviour of the mass solutes (Br^-, NO_3^-) present in the remedial solution is consistent with the transport of the contaminants within the study area. Average linear groundwater velocities for the specific units were estimated from the Br^- tracer breakthrough data.

The groundwater velocity was determined by measuring the departure of the centre of mass of the remedial solution within the injection well. The distance the centre of mass of the slug had to travel was established using the injection radius of influence (ROI) as previously described in equation (6.1). The average linear groundwater velocity, v was determined from the following distance over time relationship presented in equation (6.2) below:

$$v = \frac{ROI}{t_{0.5}} \tag{6.2}$$

Where $t_{0.5}$ is the time for the C/C_o of the BTC to be reduced to half of the maximum relative tracer concentration measured in the injection well or at the downgradient multilevel wells located in Row 1. An example of the graphical determination of $t_{0.5}$ is shown in Appendix E. The linear groundwater velocity was calculated based on the removal of the remedial solution in the injection well, MW-501 and the arrival at the downgradient network of multilevel wells MW-302 and MW-402 situated in Row 1.

Remedial test solution transport velocities were calculated for specific observation points screened in the various aquifer formations. The results of estimated values of v corresponding to individual stratigraphic units are summarized in Table 6.1. The measured horizontal hydraulic gradient at the time of the injection, determined from monitoring groundwater levels at MW-103, MW-101 and MW-107 as previously discussed, is also presented in Table 6.1. A complete evaluation of linear groundwater velocities for each multilevel sampler during injections 1 through 12 is presented in Appendix E.

Table 6.1: Method A average linear groundwater velocity estimates from the injection interval, Unit 2, Unit 3 and Unit 4 determined from MW-302 and MW-402 multilevel ports.

Injection No.	Date	Measured horizontal hydraulic gradient, i	Average Linear Groundwater Velocity (m/day)			
			Injection Interval	Unit 2	Unit 3	Unit 4
1	28-Jul-09	0.007	0.20	1.91	1.00	0.73
2	05-Aug-09	0.007	0.71	--	0.62	0.76
3	07-Aug-09	0.007	0.43	0.85	0.69	0.56
4	10-Aug-09	0.007	0.45	0.49	0.35	0.41
5	13-Aug-09	0.006	0.41	0.40	0.34	0.39
6	17-Aug-09	0.006	0.38	Dry	0.73	0.38
7	25-Aug-09	0.006	0.96	Dry	0.07	0.29
8	09-Sep-09	0.004	0.72	Dry	0.11	NA
9	24-Sep-09	0.005	0.11	Dry	0.06	0.05
10	15-Oct-09	0.003	NA	Dry	0.13	0.04
11	03-Nov-09	0.002	NA	Dry	NA	0.05
12	18-Nov-09	0.003	0.01	Dry	NA	NA

Notes:
MW-501 – sand pack in Unit 3 and screened in Unit 4 aquifer materials; Dry – groundwater elevation below screened interval of monitoring point at the time of injection; NA – measurement not application, insufficient data for analysis

In general, *v* in aquifer units 2, 3 and 4 declined during the course of the injections (Table 6.1). Analysis of the data also suggests that a few small increases in velocities inferred from the injection data as time progressed (Unit 3 following injection 6), however this observed behaviour is not consistent with the hydrogeological conditions present and the result is likely representative of the limitations of the test method. The highest groundwater velocity, v_2 = 1.9 m/day was estimated in Unit 2, followed by the upper portion of Unit 3 v_3 = 1.0 m/day and Unit 4 v_4 = 0.8 m/day. Groundwater velocities inferred from multilevel well MW-302, situated closest and directly downgradient of the injection well in the groundwater flow path, were generally greater than those determined from MW-402 (Appendix E, Tables E.3 and E.4).

The relationship between average linear groundwater velocity, inferred from Br$^-$ tracer breakthrough results and the seasonal variability of the horizontal hydraulic gradient within the study area is presented in Figure 6.13. The removal of remedial slug injected within the vicinity of the injection well is correlated with seasonal groundwater levels and horizontal hydraulic gradients which drive the transportation of the remedial plume.

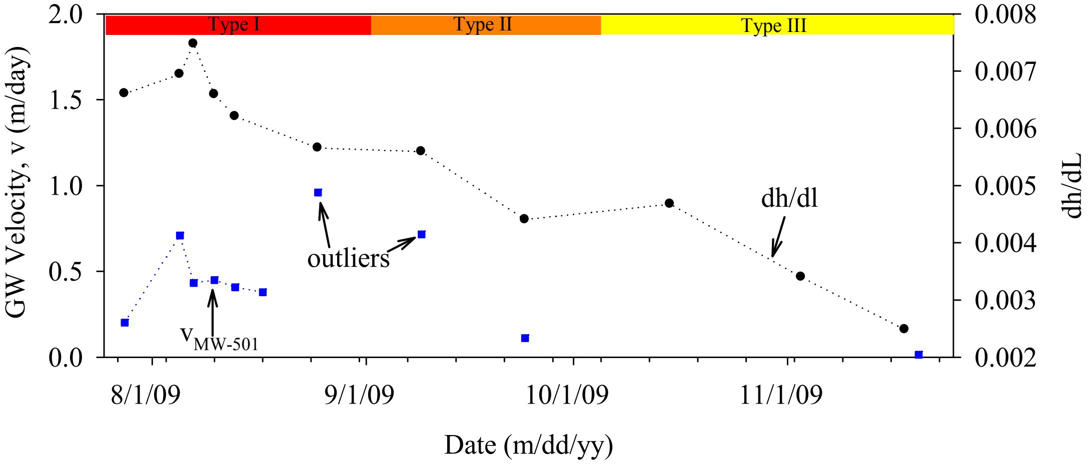

Figure 6.13: Transport velocity of remedial pulse within Unit 4 inferred from the results of the injection well MW-501 BTCs corresponding to natural horizontal gradients present at the time of each injection.

Groundwater mounding that occurred during the injection phase also created temporary artificial gradients that contributed to the rapid delivery and transport of the remedial pulse within the saturated environment, as previously discussed in Section 6.2. Groundwater monitoring conducted during the injection phase (monitored in detail during injection 12 only) indicates that the remedial solution was transmitted to the first fence of observation points in Row 1 within 26 minutes of the commencement of the injection. The injectate solution had an observed ROI of about 2 m downgradient from the injection well, which was greater than the estimated value (1.4 m) using equation (6.1). The rapid arrival of Br$^-$ tracer in Row 1 (see Fig. 6.14) translates to a maximum average linear groundwater velocity of 9 cm/min (based on MW-402-4 data) under the injection gradient ($i = 0.03$). At this time, Unit 2 and portions of Unit 3 were no longer saturated, due to the seasonal decline in groundwater levels and no groundwater samples were collected from those points. Considering Unit 4 is comprised of less conductive materials than both Unit 2 and Unit 3, it was assumed that the remedial test solution would also have arrived at the Row 1 before the completion of the injection phase during earlier injections.

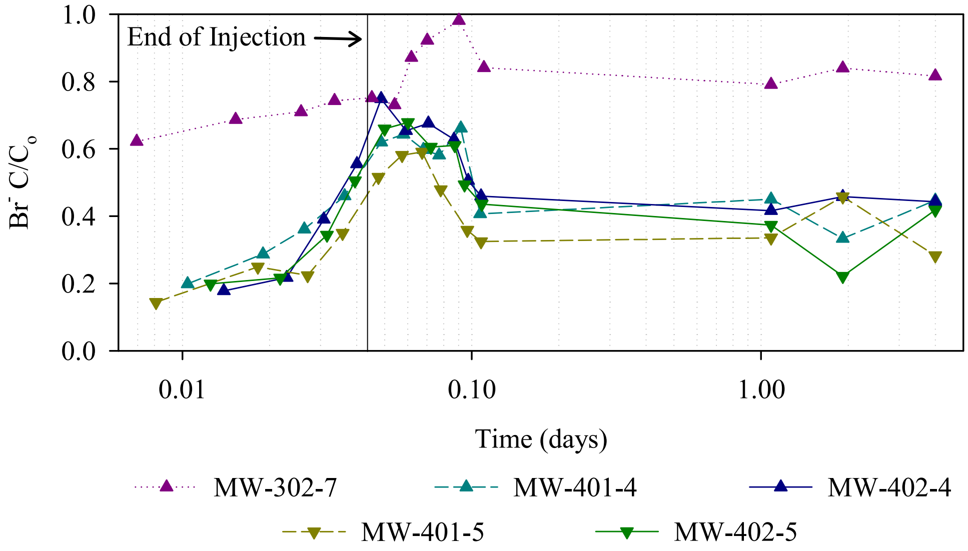

Figure 6.14: Br^- tracer breakthrough curves for select observation points screened within Unit 3 (MW-402-4 only) and Unit 4 during the injection phase and post-injection 12. Note that background $C/C_o > 0$, originating from previous injection events that contributed to the continuous plume of TEA amended water.

The Br^- tracer arrival, residence times and peak concentrations were similar for MW-401-4, MW-401-5, and MW-402-5, all situated in Unit 4. The most rapid Br^- arrival was observed in MW-402-4 located in Unit 3. The arrival of the tracer in MW-302-7 was delayed compared to the other points, despite this location having the greatest normalized concentration. The amount of Br^- tracer recovered in all three multilevel wells increased from pre-injection conditions once the peak pulse passed. Maximum Br^- concentrations (pre- and post-injection) within the multilevel wells differed, reflecting variable degrees of dispersive mixing of the injectate slug with the “background” groundwater.

The relative percent increase between C/C_o observed pre-injection and peak concentrations at MW-302-7 was approximately 50%, compared to a 100% increase in MW-401 and MW-402. Similarly, Br- tracer remaining following the migration of the peak concentrations observed as a result of the injection declined by approximately 40% at MW-401 and 402 and only 22% at MW-302 over the same period of time.

6.5 Remedial Tracer Test Summary

The delivery of the remedial test solution to a target zone of the aquifer contaminated with residual petroleum hydrocarbons was evaluated by monitoring groundwater for Br^- tracer. The injectate was also amended with nitrate serving as a TEA and reactive tracer to enhance in-situ biodegradation in the petroleum hydrocarbon contaminated residual zone of the anaerobic aquifer. The results of the Br^- tracer breakthrough data provide insight into the groundwater transport processes, the subsequent transport of mass contaminants and remedial solution present at the Site under variable hydrogeological conditions. Details pertaining to the delivery and utilization of nitrate in the degradation of petroleum contaminants from denitrification are discussed in Chapter 7.

Chapter 7: Remediation System Evaluation

7.1 Delivery of Remedial Solution amended with TEA to Target Zone

The remedial test solution was amended with a conservative tracer (Br^-) and NO_3^- which serves as a terminal electron acceptor (TEA) in the microbial degradation of petroleum hydrocarbons in the saturated environment. The delivery of the remedial solution to the subsurface was documented by groundwater monitoring for the presence of Br^- tracer within a network of multilevel wells. The reactive NO_3^- behaves similarly to the conservative tracer in that it is readily transported within the subsurface by groundwater flow and concentrations are transformed by hydrodynamic dispersion. NO_3^- transport within the groundwater flow system is not inhibited by sorption processes; however NO_3^- may be utilized by indigenous microbial communities as a TEA in the biodegradation of petroleum hydrocarbons resulting in NO_3^- mass removal and reduced concentrations in the groundwater. Groundwater samples were collected within the remediation network at various times and analyzed for the reactant nitrate and nitrite (NO_2^-), an intermediate biodegradation product of denitrification of petroleum hydrocarbons.

As previously discussed in Chapter 6, the remedial test solution was delivered into the saturated zone containing residual petroleum hydrocarbons in a short period of time to produce a cloud of TEA amended water within the target area. The introduction of a large pulse of treatment water into the subsurface resulted in the amended water displacing and mixing with existing petroleum contaminated groundwater within the vicinity of the injection well. Considering the high degree of residual contamination within the study area, it is assumed that the injection of non-impacted water would contribute to the dissolution of contaminants sorbed to the aquifer materials.

The results of the groundwater monitoring program measuring Br^- indicate the remedial solution was delivered to aquifer materials containing residuals between at least 306.2 and 301.5 m AMSL, exceeding the originally targeted depth interval of 305 to 302 m AMSL (see Fig. 7.1).

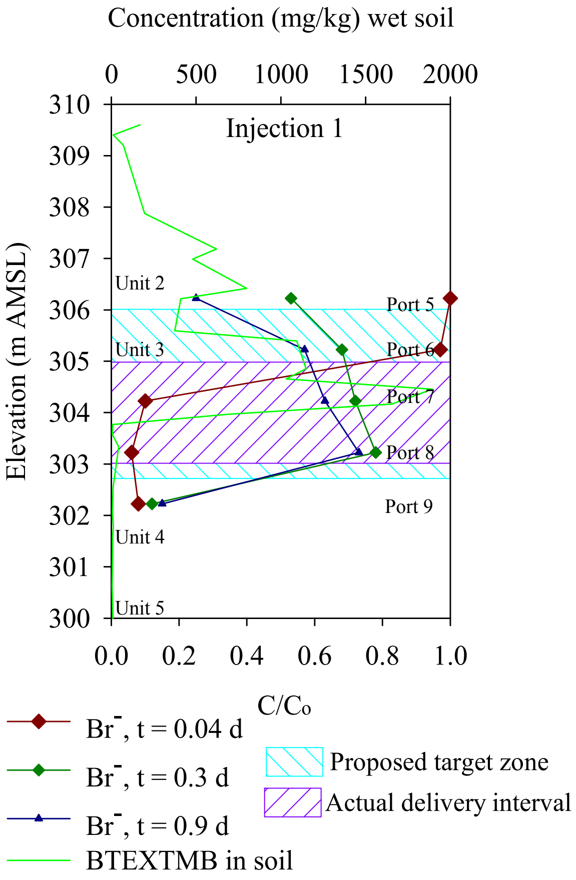

Figure 7.1: Vertical distribution of the remedial solution at times (t) 0.04, 0.3 and 0.9 days (as inferred from normalized Br- concentrations) and background BTEXTMB soil concentrations at BH/MW-302 (2 m from MW-501). The target zone contained residual petroleum contaminants; with BTEXTMB soil concentrations exceed 13 mg/kg.

7.2 Mass Flux of Remedial Tracer Solution

The successful delivery of the remedial solution amended with TEA to the select depth interval impacted with residual petroleum hydrocarbons was confirmed with the estimate of the mass flux of remedial solution transported through the various formations within the study area. The Mass Flux Calculation Method entails measuring the total tracer mass flux across a transect determined by the cross-sectional area of multilevel wells downgradient of injection well MW-501 in rows 1, 2 and 3 at a certain moment in time as previously described in Chapter 5. The distribution of the percentage of Br^- tracer recovered using the Mass Flux Calculation Method is presented in Figure 7.2.

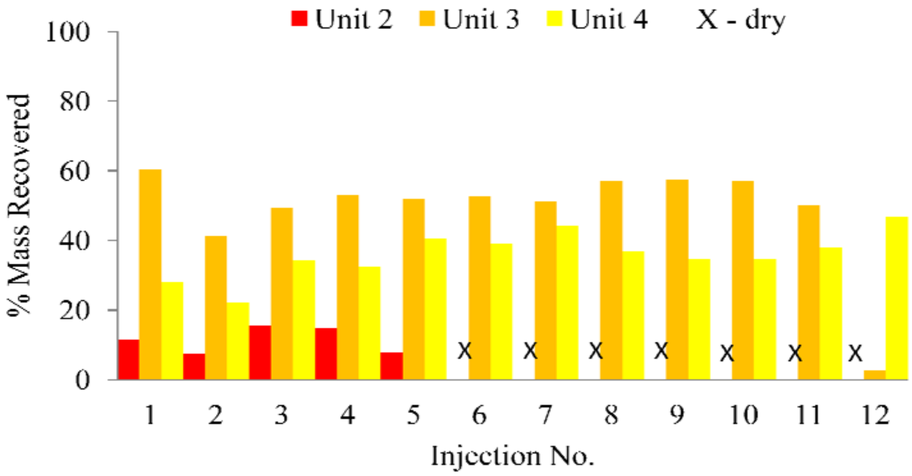

Figure 7.2: Mass flux of Br- recovered in row 1 of the remedial monitoring network comprised of multilevel wells MW-302, MW-401 and MW-402 screened within Unit 2, Unit 3 and Unit 4.

The remedial solution was primarily transported through Unit 3 and Unit 4, consistent with the delivery interval. Approximately 55% of the residual tracer mass flux was recovered in Unit 3, 40% in Unit 4 and 5% in Unit 2. The percent residual tracer mass flux recovered in Unit 2 is not necessarily representative of the amount of remedial solution delivered to the area based on the limited area included in the analysis (represented by a single monitoring point). However, it must also be noted that groundwater elevation dropped below Unit 2 from Injection 6 onwards, resulting in the monitoring point no longer serving a purpose. The mass flux of Br^- tracer solution was consistently higher in Unit 3 compared to Unit 4, except for during Injection 12, when the formation was subject to a seasonally low water table and several multi-samplers in Unit 3 were situated in the unsaturated zone at this time. In general, the Unit 3 sand and gravel aquifer materials were more permeable than sandy Unit 4, resulting in a slightly greater mass flux within this formation as seen in Figure 7.2.

Moment analysis was also used to determine the amount of Br^- mass recovered in the downgradient monitoring rows 2 and 3. The mass of the conservative tracer injected in the subsurface remains constant, however observed concentrations may be reduced due to hydrodynamic dispersion. The percentage of Br^- tracer recovered post-injection was 87% in Row 1, while tracer recovery in Row 2 and 3 situated further downgradient was less than 10%. The percent difference between the amount of tracer recovered in rows 2 and 3 exceeds the acceptable 10% experimental uncertainty. Low measured concentrations and limited Br^- tracer recovery may be attributed to dilution, dispersion and sampling ports situated beyond the direct flow path of the injected slug.

7.3 Enhanced Bioremediation of the Petroleum-Impacted Residual Zone

7.3.1 Measurements of Degradation

The remedial test solution was amended with increasing concentrations of NO_3^- (90 to 265 mg/L) throughout the series of injections to permit the acclimatization of the indigenous microbes present in the contaminated aquifer to the artificially enriched TEA conditions. Groundwater samples were collected for NO_3^- analysis at the same frequency as the Br^- tracer. However, only select samples were selected for analysis based on elevated Br^- concentrations, which indicated zones where significant amounts of remedial test solution were delivered. Measured concentrations of NO_3^- were normalized to Br^- values in order to account for depreciated concentrations attributed to dispersive dilution processes.

The arrival and departure of the tracer species for Injection 6 screened within Unit 3 at observation points MW-302 Port 6 and MW-402 Port 2 is presented in Figure 7.3. The behaviour of the tracers within the injection well and MW-302 Port 7 following Injection 12 are illustrated in Figure 7.4 screened within Unit 3 and 4 and 4, respectively. The arrival front of Br^- coincides with that of the NO_3^- reactive tracer. During both injections, the Br^- arrival had a higher peak than the reactive-biodegradable NO_3^- tracer. The differences in peak concentrations between Br- and NO_3^- is attributed to NO_3^- mass removed by microbial consumption as both species were subject to the same hydrodynamic dispersion processes. The discrepancy between the depleted concentrations observed between the conservative and reactive tracers in Figures 7.3 and 7.4 is likely the result of biological activity carrying out denitrification.

Comparison between the results of the earlier Br^- and NO_3^- breakthrough curves presented in Figure 7.4 reveal that concentrations of NO_3^- are rapidly reduced to trace amounts within 3 days, while the Br^-

curve gradually tails off at elevated concentrations ($C/Co < 0.10$). During the final injection at 265 mg/L NO_3^- (Fig. 7.4), NO_3^- concentrations were depleted after approximately 20-25 days. Measured concentrations of NO_3^- downgradient of the injection source in Row 1 were highest during the final injection and more closely related to values of the conservative tracer, where the relative difference between Br^- and NO_3^- was approximately 22% for Injection 6 compared to <7% for injection 12.

Degradation rates following injections 6 and 12 were calculated as described in Chapter 5, and were calculated following Injection 6 and 12 are presented in Figures 7.5 and 7.6, respectively. Denitrification follows a first-order kinetics reaction where NO_3^- concentrations are low compared to the organic substrate, which is consistent with the conditions present at the Site. The average first-order denitrification rate (k_{NO3-}) measured 0.72 ± 0.07 day^{-1} in the sand and gravel aquifer materials of Unit 3 (Fig. 7.5) during injection 6. Lower first-order denitrification rates were observed for Injection 12 when the remedial test solution was amended with greater concentrations of TEA, where $k_{NO3} = 0.10 \pm 0.002$ day^{-1} for the injection well test interval between sandy gravel and sand materials (Unit 3 and Unit 4) and $k_{NO3} = 0.16 \pm 0.01$ day^{-1} for downgradient monitor MW-302-7 screened within Unit 4.

Quantifying denitrification is challenging due to the high spatial and temporal variability of the process (Foloronuso & Rolston 1984, Burton and Beauchamp 1985, Robertson and Tiedje 1985, Parkin et al. 1987, Robertson et al. 1988). In general, denitrification rate coefficients calculated from the two injections are not comparable given the different hydrogeological setting and flow conditions present at the time of each respective injection: high water table and groundwater flow (Injection 6), compared to seasonal low water table and reduced groundwater flow (Injection 12).

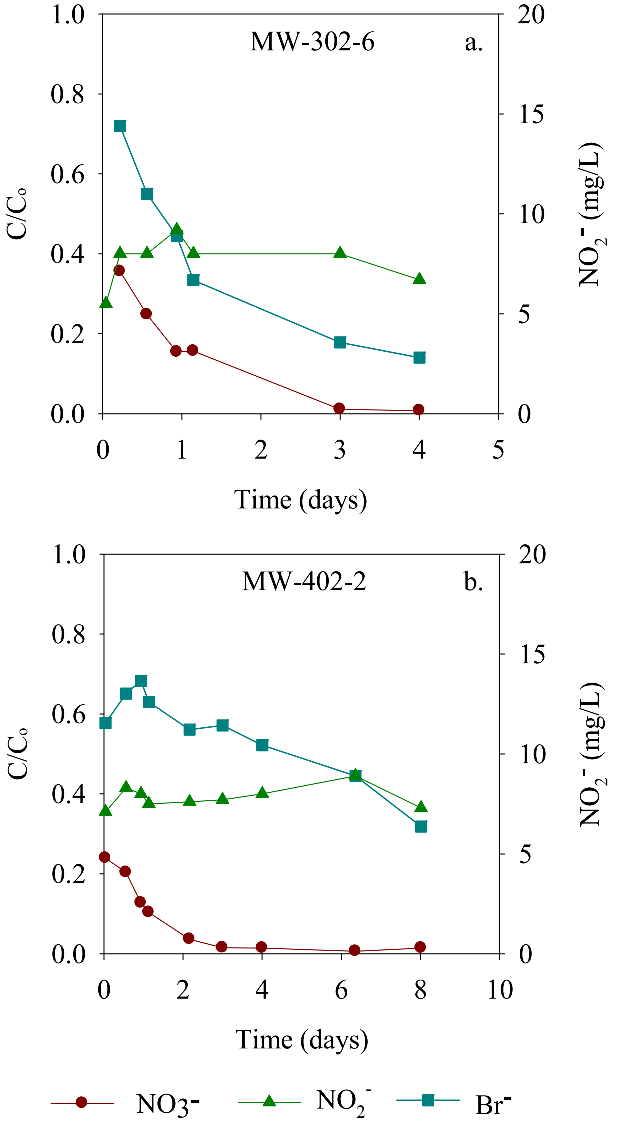

Figure 7.3: Normalized concentrations of Br$^-$, NO$_3^-$ and concentration of nitrite of select downgradient multilevel wells MW-302-6 and MW-402-2 screened within Unit 3 during Injection 6.

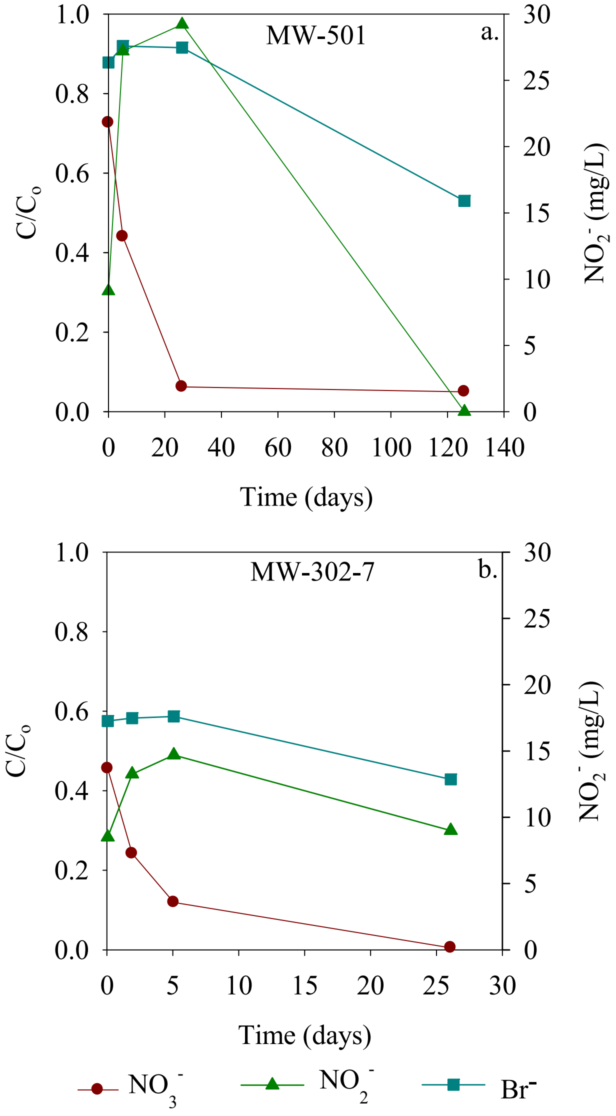

Figure 7.4: Normalized concentration of Br$^-$, NO$_3^-$ and the concentration of nitrite occurring in the injection well MW-501 and downgradient multilevel well MW-302-7 screened partially within Unit 3 and 4 (a) and within Unit 4 (b) during injection 12.

The temperature of the remedial test solution may also have significantly influenced the measured rates of denitrification for the two injections. The field preparation of the remedial test solution occurred within a shelter and out of direct sunlight, however it was susceptible to ambient environmental conditions at the time of the injection. Higher rates of denitrification were estimated when the injectate was approximately 20°C during injection 6, compared to 10°C during injection 12 and equivalent to the average groundwater temperature . Nester et al, (2001) established the notion that the speed of enzymatic reactions in the cell approximately doubles for each 10 ^{o}C rise in temperature to an upper limit that the microorganisms can withstand. Petroleum degraders present in the subsurface typically consist of mesophiles, which have an optimum temperature ranging from 25^{o}C to 45^{o}C (Nester et al., 2001).

Nutrients, electron acceptors or substrate availability can be limiting to biodegradation reactions. Rates of denitrification within the aquifer are also influenced by several factors including the spatial and temporal variations in conditions such as organic contaminants serving as electron donors (petroleum hydrocarbons), availability of TEA to indigenous microbial populations (including concentration of nitrate delivered over time). Higher concentrations of NO_3^- may also increase the rate of diffusion to anaerobic sites, increasing the availability of the terminal electron acceptor to indigenous denitrifying microbes.

Subsurface heterogeneity also influences the flow direction, flow velocity and the residence time of the TEA amended remedial solution with microbial populations present within the subsurface. Alter et al. (2003) reported a greater amount of reactive tracer removed in wells screened within less permeable materials. Increased contact times between bacteria and contaminants are associated with higher biodegradation rates as demonstrated in column studies (Angley et al., 1992; Brusseau et al., 1999). In contrast, the availability of microbial populations may also be limited in the finer grained sediments of Unit 4, where sulphate reducing bacteria have a size range of 0.5-1 μm possibly too big to pass through the pore spaces (Fredrickson et al, 1997). However, the results of the field experiments are not consistent with these findings as higher rates of denitrification (injection 6, k_{NO3}= 0.77 ± 0.07 day^{-1}) were measured in the more permeable materials of Unit 3 compared to Unit 4 (injection 12, k_{NO3}= 0.16 ± 0.07 day^{-1}) when concentrations as great as 265 mg/L NO_3^- were used. Ryden & Lunden (1980) and Limmer & Steele (1982) also indicated that denitrification rates can be controlled by available carbon serving as an electron donor as opposed to NO_3^- concentrations, influenced by the properties of the porous media, composition and distribution of the organic contaminants.

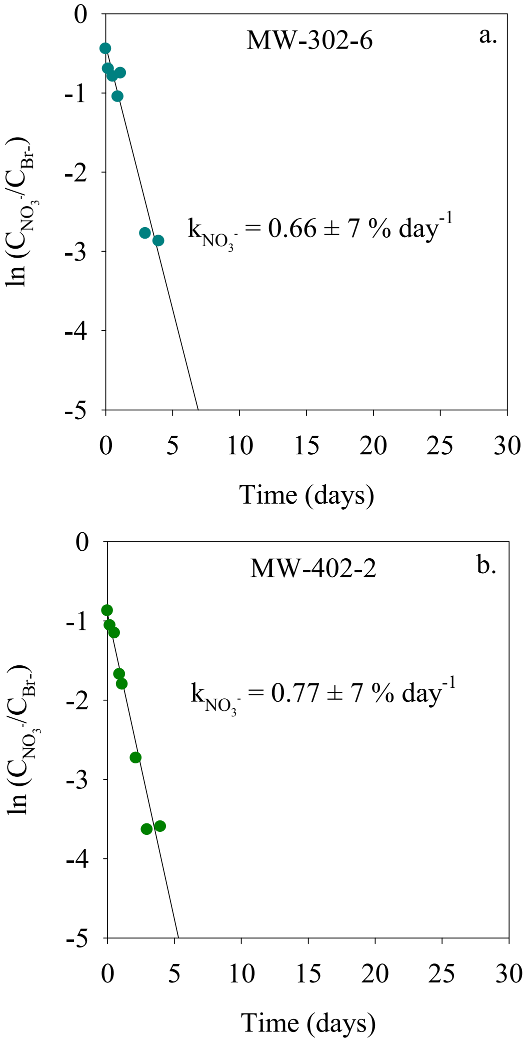

Figure 7.5: Calculated first-order nitrate degradation in Unit 3, from Figures 7.4a and b for downgradient multilevel wells MW-302 Port 6 (a) and MW-402 Port 2 (b) following Injection 6. The remedial test solution was amended with 90 mg/L NO_3^-.

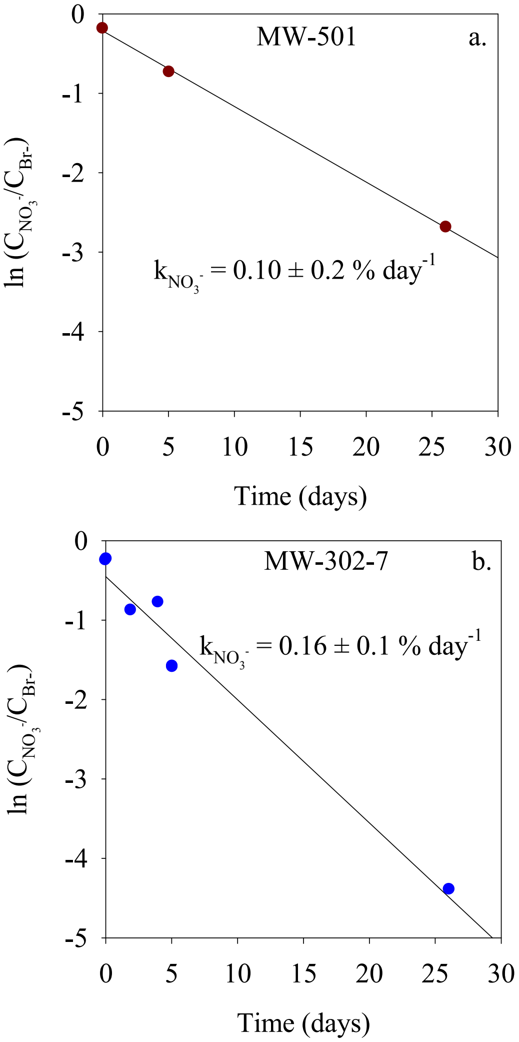

Figure 7.6: Calculated first-order degradation of nitrate at the injection well within Unit 3 and Unit 4, from Figures 7.5a and b for MW-501 (a) and downgradient monitor MW-302-7 (b) following Injection 12. Remedial test solution amended with 265 mg/L NO_3^-.

7.2.2 Denitrification Intermediate Products

Microbial utilization of NO_3 was also inferred by measuring concentrations of NO_2 in the groundwater, an intermediate product of denitrification (Postma & Appelo, 2005). Measured concentrations of nitrite as nitrogen (NO_2-N) in groundwater within the study area prior to remedial solution injections were <1 mg/L NO_2-N.

An increase and eventual decline in NO_2^- concentrations versus time were measured following injection 6 and 12, as illustrated in Figures 7.3 and 7.4, respectively. Nitrite present in the area infused with the remedial test solution was observed following several pulsed injections of TEA amended water. Concentrations of NO_2^- remained fairly consistent in downgradient monitors following injection 6, with an average value of 8 mg/L, despite declining concentrations of reactive and conservative tracers, Figure 7.3. Greater concentrations of NO_2^- were measured following injection 12, as high as 30 mg/L in the injection well and 15 mg/L in the downgradient monitor as illustrated in Figure 7.4.

Kuhn et al. (1988) found that NO_2^- exhibited toxic effects when above 5 mM (200 mg/L) to microbial populations degrading toluene, which is significantly higher than the maximum observed in the field of 0.7 mM (30 mg/L). Microbial toxicity effects related to temporary elevated amounts of NO_2^-produced during denitrification are not anticipated to occur within the study due to the low levels generated. Declining concentrations of NO_2^- were observed in the injection well and downgradient monitor when levels of NO_3^-, serving as the primary TEA, were depleted (Fig. 7.4). The denitrification process continues with the microbes utilizing NO_2^- as a TEA (Postma & Appelo, 2005) for metabolic processes, whereby depleting NO_2^- concentrations observed in Figure 7.4 may be attributed to dilution attributed to aquifer dispersion in addition to mass removed related to biological activity.

Nitrate removal in the groundwater system may be the result of processes other than NO_3^-assimilation or respiratory denitrification. Dissimilatory nitrate reduction to ammonium (DRNA) involves the microbially mediated transformation of NO_3^- to ammonium (NH_4^+) as opposed to assimilatory processes that utilize nitrogen (N) towards microbial biomass. Geochemical analysis of groundwater sampled within the radius of influence of the injectate (MW-302-7) revealed 3.3 mg/L NH_4^+ present approximately 181 days following the final injection. Nitrate is reduced to ammonium under anaerobic conditions when biochemical demands involve a highly reduced environment and excess organic carbon (eg. Freeze & Cherry, 1979; Keeney, 1989), which are consistent with the conditions at the Site. The DNRA process may result in the production of NH_4^+ that can then be assimilated into cellular constituents (Schilling, 2002) or adsorbed on silt and clay-sized particles in the aquifer (DeSimone & Howes, 1998; Freeze & Cherry, 1979). The relatively low concentration of NH_4^+ measured in the study area compared to the concentrations of NO_3^- in the injectate indicates that NH_4^+ production as a result of the NO_3^- amendment may be occurring in the subsurface, however not in significant amounts considering the stoichiometry of DNRA as previously discussed in Chapter 1, equation (1.5).

7.2.3 Biostimulation of Indigenous Microbial Populations

Groundwater samples were collected on April 27, 2009 from multilevel wells MW-301 Ports 7, 12 and MW-302 Port 7, situated upgradient and downgradient of the injection well, respectively, to establish background microbial numbers prior to the installation of the injection well and subsequent delivery of remedial test solution to the subsurface. Post-injection groundwater samples were collected on November 3, 2009 following 10 injections and on April 27, 2010 to assess changes in the abundance of microbes present within the study area following the addition of an artificial supply of NO_3^-.

Aerobic heterotrophic plate counts (HPC) were conducted to establish pre- and post-injection microbial populations present in the groundwater system within the select remedial zone. The HPC method provides an estimate of the number of bacteria present in a known volume of water measured in colony forming units per milliliter (CFU/mL). However, microbial plate enumerations can be quite variable (Riser-Roberts, 1992) as most microbes in the groundwater system are attached to sediments. The results of the HPCs pre- and post-injection of remedial solution are summarized in Table 7.1.

Table 7.1: Results of microbial enumerations (CFU/mL) of groundwater water sampled from the study area pre- and post-injection determined by the HPC method.

Monitoring Well Date	Pre-Injection 27-Apr-09	Post-Injection 1 3-Nov-09	Post-Injection 2 27-Apr-10
MW-301-7[1]	11	530	--
MW-301-12[1]	900	290	--
MW-302-7[2]	64	61	--
MW-501[3]	--	38	23,000
MW-401-5[2]	--	>5,700	--
MW-402-3[2]	--	>5,700	--
MW-402-4[2]	--	>5,700	--
MW-103[4]	--	--	960
MW-4[4]	--	--	360

[1] situated upgradient of injection well MW-501, [2] downgradient of MW-501 in Row 1, [3] injection well, MW-501
[4] situated beyond the radius of influence of the remedial test solution within anaerobic petroleum hydrocarbon impacted aquifer

In general, microbial numbers increased following the injection of TEA amended remedial test solution to stimulate the biodegradation of petroleum contaminants. Field observations indicate that groundwater samples collected from MW-301-7 and MW-501 had high sediment loadings, whereby the plate count numbers could include bacteria associated with the aquifer materials that were settled out as opposed to the water matrix that was used in HPC analysis, thus resulting in higher counts. Laboratory and field experiments have indicated that most microbes preferentially adhere to geologic material and have a low propensity for transport (e.g. Deflaun et al., 1997, Harvey, 1997).

Actual microbial counts are likely even greater than what was determined using the HPC analysis following pre- and post-biostimulation of the petroleum hydrocarbon impacted anaerobic aquifer, especially in regards to MW-301-7 (pre-injection), MW-302-7 (pre- and post-injection) and MW-501 (post-injection 1 only). Typically, more than 25% of the microorganisms isolated in the groundwater sample will fail to grow on subculture on an artificial medium (Stetzenbach et al, 1985). Not all organisms capable of degrading petroleum hydrocarbons will be able to grow on the growth media used in for the HPC, especially in regards to subsurface microbes having unknown growth requirements that aren't accounted for in the growth media (Wilson et al., 1986).

The findings of the microbial counts indicate significantly higher numbers in the injection well as opposed to PHC impacted wells MW-103 and MW-4, which were not subject to enhanced in-situ bioremediation treatment. The microbial counts determined using the HPC technique to do not differentiate between viable populations and hydrocarbon degraders. However, ratios of hydrocarbon utilizers to viable heterotrophs show dominance of hydrocarbon utilizers in gasoline-contaminated sediment (Horowitz, Sexstone & Atlas, 1978) and counts of hydrocarbon degraders are higher in soil amended with nitrogen and phosphorus (Huesemann & Moore, 1993). Considering a mature petroleum hydrocarbon source zone is established at the Site, it is assumed that the apparent increase in microbial count likely included petroleum degraders as well.

7.2.3 Alternative Electron Acceptors

Nitrate introduced to the anaerobic environment during consecutive injections likely served as the primary terminal electron acceptor in the biodegradation of petroleum hydrocarbons within the residual zone. Given the large mass delivered to the target area throughout pulsed injections, a sustainable supply of TEA was provided to the microbes in order to effectively acclimatize to the NO_3^- rich conditions and be preferentially utilized in the degradation of petroleum hydrocarbons. Previous geochemical analysis of groundwater analyzed within the aerobic (non-petroleum hydrocarbon, PCH) and anaerobic (PHC-impacted) aquifer reveal that naturally occurring potential TEAs such as SO_4^{2-} and dissolved O_2 in addition to Fe(III). These additional TEAs may also have contributed the partial removal of contaminants accompanying the denitrification processes during the field experiment. Geochemical analysis of groundwater sampled from MW-501 post-injection is presented in Table 7.2.

Table 7.2: Results of the post-injection geochemical analysis of groundwater sampled within the study area, including concentrations of alternative TEAs or electron donors to NO_3^-.

Well ID	Date	Dissolved O_2	Dissolved Fe	Dissolved Mn	NO_3-N	SO_4^{2-}	Dissolved CH_4
RDL			*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
MW-501	24 Apr-10	<1	3.9	0.2	<0.1	15	0.42

The remedial test solution was sparged with nitrogen gas to ensure the dissolved O_2 content was < 1 mg/L (anoxic) prior to being injected into the anaerobic aquifer in order to mitigate the preferential utilization of the metabolically favourable O_2 as a TEA as opposed to NO_3^-. Monitoring of dissolved O_2 levels pre and post-injection revealed that the target remedial zone of interest remained anaerobic throughout the injections, thus O_2 was not present in sufficient quantities to preferentially serve as a TEA.

The remedial test solution was composed of municipal supply water amended with conservative and reactive tracers. The prepared remedial test solution had concentrations of SO_4^{2-} between 53-63 mg/L as a result of naturally occurring sulphate in the water supply (see Appendix F). Historical background concentrations of 30 mg/L of SO_4^{2-} have been observed at MW-109 (non-impacted aerobic aquifer), while concentrations up to 2 mg/L SO_4^{2-} have been detected in MW-103 situated in the petroleum-contaminated anaerobic aquifer (SNC Lavalin, 2008) as previously discussed in Chapter 2. The behaviour of the declining concentrations of SO_4^2 was similar to the Br^- tracer following injections 6 (Fig. 7.7) and 12 (Fig. 7.8) compared to reactive NO_3^- at select downgradient multi-samplers and within the injection well.

Sulphate measured in MW-501 (72 mg/L) 26 days following injection 12 exceeded the amount present in the injection solution (53 mg/L) (Fig. 7.8). Groundwater samples were collected at MW-501 and analyzed for geochemical parameters on April 24, 2010, approximately 154 days following injection 12. Sulphate concentrations declined to 15 mg/L ($C/C_o = 0.3$) by this time, whereas the concentration of Br^- tracer was 126 mg/L ($C/C_o = 0.5$) which may be an indicator that SO_4^2 reduction has occurred. When SO_4^2 is reduced, iron sulphide (FeS) precipitates resulting in a decrease in Fe^{2+}. Following the injection of NO_3^- into the aquifer, groundwater within the zone of influence of the remedial solution, black FeS precipitate was observed in several of the multilevel samplers, which provides evidence that the study environment is anaerobic and sulphate reduction is occurring.

The variable reduction in SO_4^{2} observed during the remedial plume's drift phase provides evidence to suggest that indigenous microbial populations may be utilizing SO_4^{2} as an alternative electron acceptor to NO_3^- in the enhanced degradation of organic contaminants. However, SO_4^{2-} was not present in significant quantities to serve as the primary TEA in the biodegradation of petroleum hydrocarbons. Nitrate is more energetically favourable and preferentially utilized by the microbes in the oxidation of organic contaminants compared to sulphate (e.g. Mackay & Cherry, 1989; Ball & Reinhard, 1996) and a continuous abundant supply of NO_3^- was provided to the microbes during the 121 day period when 12 injections of remedial solution took place.

Sulphate utilization may become significant when NO_3^- levels have been substantially depleted by redox processes and a sustainable supply is no longer present. The degradation of benzene is described by the following equation 7.1 (Borden et al., 1995):

$$C_7H_8 + 4.5SO_4^{2-} + 3H_2O_{(l)} \rightarrow 2.25H_2S_{(g)} + 2.25HS^- + 7HCO_3^-{}_{(l)} + 0.25H^+ \qquad (7.1)$$

The use of sulphate as a terminal electron acceptor will result in increases of carbonate (HCO_3^-) and hydrogen sulphide (H_2S) concentrations however, neither were measured during the field experiment.

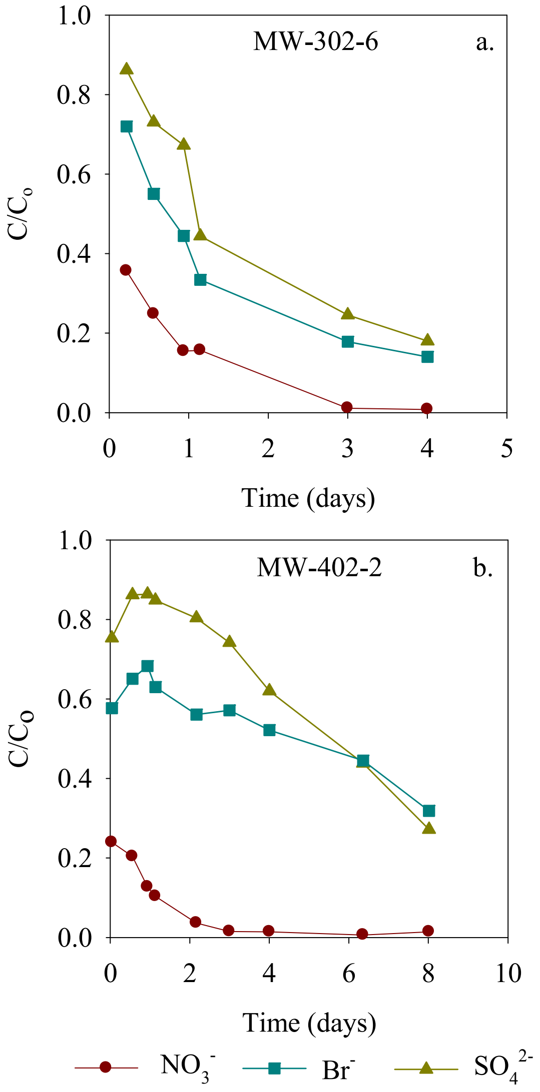

Figure 7.7: Comparison between the behaviour of conservative and reactive tracers, Br^-, NO_3^-, and potential alternative TEA, SO_4^{2-} present in the remedial test solution originating from the municipal water supply in downgradient monitorsMW-302-6 and MW-402-2 measured during injection 6.

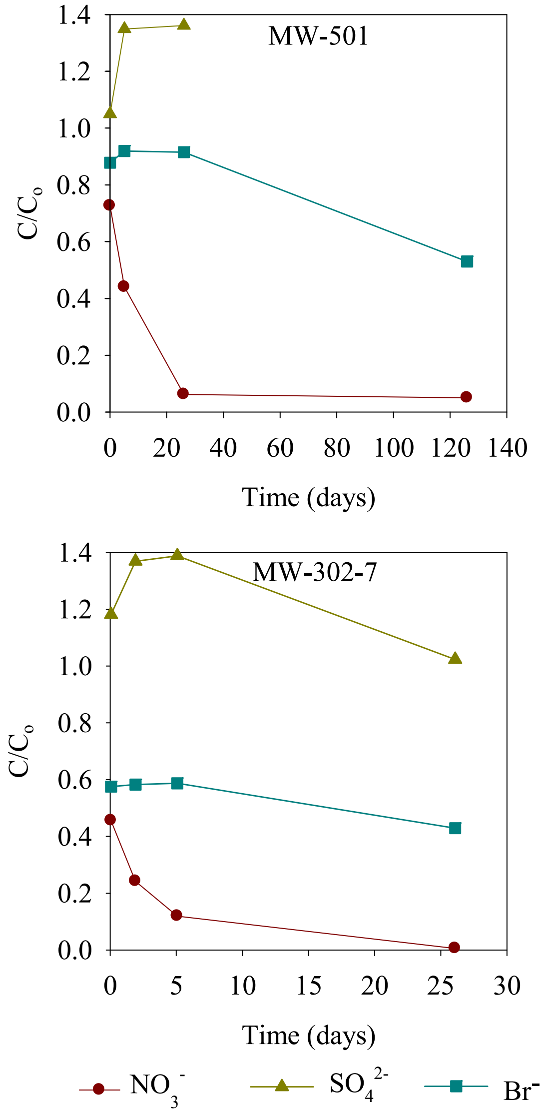

Figure 7.8: Comparison between the behaviour of conservative and reactive tracers, Br^-, NO_3^- and potential alternative TEA, SO_4^{2-} present in the remedial test solution originating from the municipal water supply in the injection well (a) and downgradient monitor MW-302-7 measured during injection 12.

Ferrous iron, Fe (II) may also serve as a NO_3^- sink in the aquifer as NO_3^- may be used as a TEA in the reduction of ferric iron, Fe (III). Dissolved ferrous iron is oxidized to Fe(III), which is insoluble and tends to be fixed to the aquifer sediments. As previously discussed in Chapter 2, iron reducing bacteria have been identified in both the aerobic and anaerobic zones of the aquifer (SNC Lavalin, 2008). The remedial test solution amended with soluble NO_3^- would be preferentially utilized as a TEA for the biodegradation of organic contaminants compared to Fe(III) because NO_3^- thermodynamically yields a greater amount of energy (eg. Lovley & Chapelle, 1995). A concentration of 3.9 mg/L dissolved iron was measured in the study area post-injection, which is consistent with pre-injection measurements of 4.4 mg/L dissolved iron in the petroleum hydrocarbon impacted aquifer (sampled from MW-103 on May 5, 2008) leading to the conclusion that Fe(III) likely did not play a significant role in the removal of NO_3^- within the study area.

7.3 Post-Injection Assessment of Subsurface Contaminants

Pre-treatment measured concentrations of BTEXTMB in the groundwater and soil were as great as 40 mg/L and 2,700 mg/kg, respectively and significantly higher than the maximum concentration of nitrate in the remedial test solution (265 mg/L NO_3^-). Dissolved contaminants were likely preferentially removed first, where the rate of transformation is limited by the rate of dissolution of the contaminants from the residual phase.

Considering only a fraction of NO_3^- was added to the contaminated aquifer to serve as a TEA in the microbially mediated degradation of petroleum hydrocarbons in a select residual zone of the aquifer, gasoline constituent toluene was specifically used to assess the potential mass of contaminants removed through denitrification in the dissolved and residual phase. Toluene is readily degraded under anaerobic conditions using NO_3^- and soil microbes have been known to metabolize concentrations of toluene up to at least 93.5 mg/kg soil/day (Ramanand, Balba & Duffy, 1995) under denitrifying conditions following acclimation. Results of the post-injection analysis of BTEXTMB were also considered.

7.3.1 Post-Injection Groundwater Sampling Results

Groundwater sampling was conducted in April 2010 to establish the conditions of the dissolved contaminant plume within the study area following the application of remedial activities. Groundwater samples were collected at discrete intervals throughout the monitoring network and analyzed for gasoline constituents of interest. The contaminants present in the dissolved phase originated from groundwater flowing through the source zone and coming into contact with residual NAPL. The amount of contaminant mass present in the groundwater is orders of magnitude less than quantities present the soil phase, however the mass of contaminants present in the dissolved phase is still of significance in regards to groundwater quality compliance standards.

Reported concentrations of toluene in the contaminant plume have been as high as 6.5 mg/L. The remedial test solution as amended with concentrations between 90 and 265 mg/L NO_3^-. The stoichiometry of the biologically mediated denitrification reaction using toluene (C_7H_8) as the electron donor was previously discussed in Chapter 5 using equation (5.2). Based on the relationship of 7.2 moles NO_3^- required to degrade 1 mole C_7H_8, the remedial solution would be capable of providing the microorganisms with enough TEA to remove concentrations of toluene between 20 and 55 mg/L assuming the reaction goes to completion and assuming there were no other NO_3^- sinks (other BTEXMB).

The historical groundwater results for select multilevel wells MW-302 and MW-303 including the post-injection groundwater sampling event are presented in Figures 7.9 through 7.12, representing the measurements of toluene and total BTEXTMB compounds. Groundwater monitor MW-303 is situated beyond the apparent influence of the remedial plume and serves as a point to comparing pre- and post-injection non-remediated groundwater sampling results (Fig. 7.9 and 7.11).

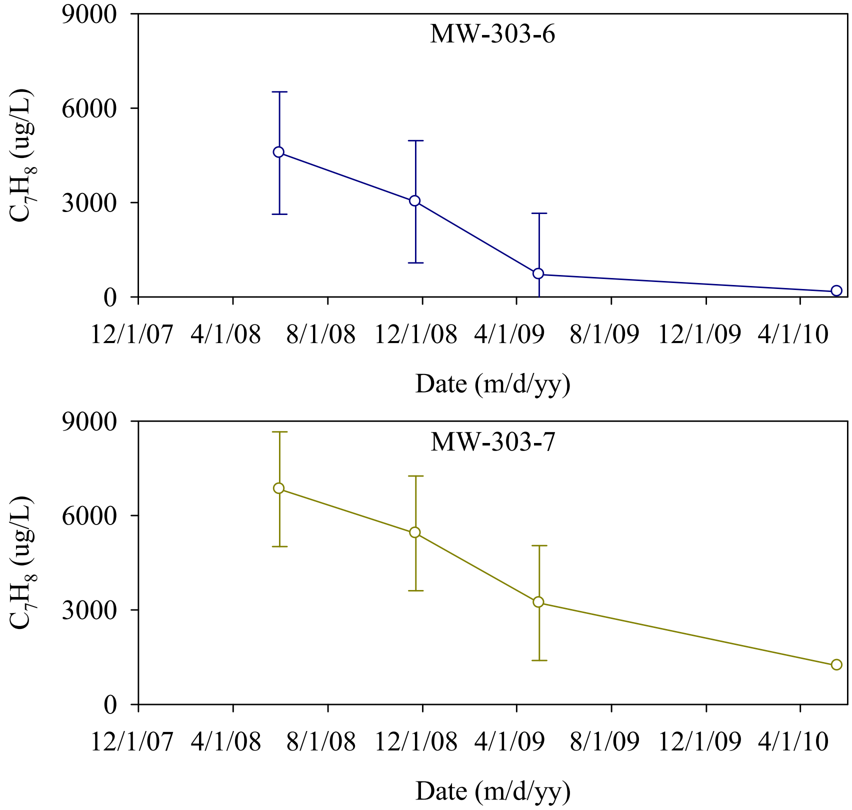

Figure 7.9: Historical results of toluene (C_7H_8) present in the groundwater at MW-303 in Ports 6 and 7 screened between 305.3 and 305.1 m AMSL and 304.3 and 304.1 m AMSL, respectively. Error bars denote typical seasonal fluctuations in measured concentrations of toluene attributed to the transient hydrogeological conditions that exist at the Site.

MW-302 consistently received TEA amended treatment water as it is located in the zone of influence of the injectate (Fig. 7.10 and 7.12). Toluene concentrations at both groundwater monitors declined considerably following the injection of the remedial solution. The addition of NO_3^- likely contributed to the removal of toluene at MW-302 to some degree. A decline in toluene at MW-303 observed, similarly to a decline in MW-302 (impacted by remedial plume), therefore the observed decline in toluene concentrations at MW-303 cannot be attributed to denitrification considering the monitor was located beyond the extent of the remedial plume.

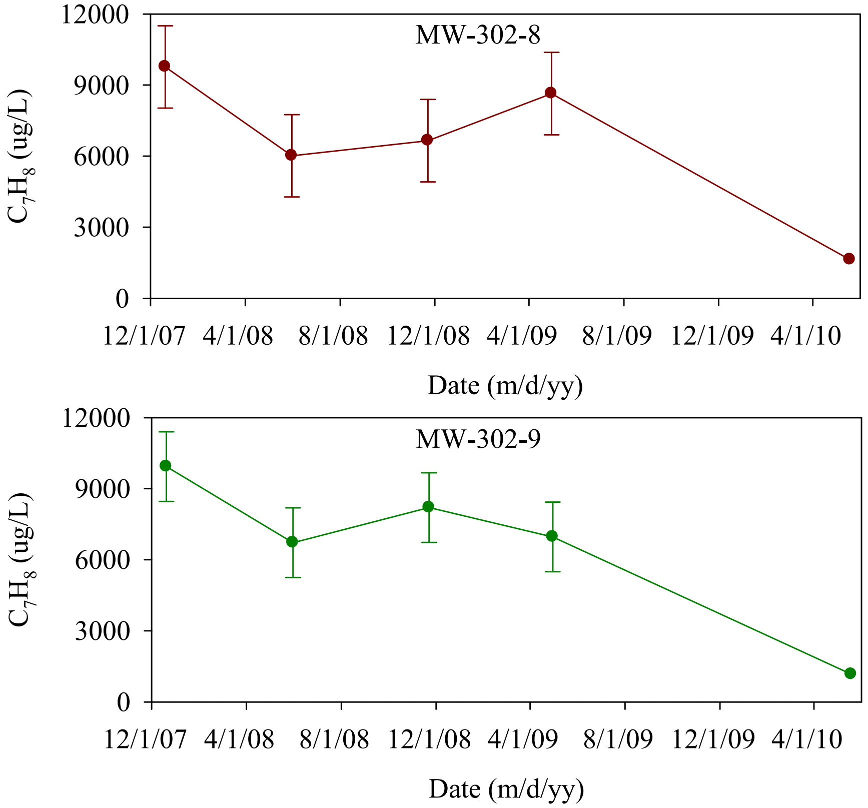

Figure 7.10: Historical results of toluene (C_7H_8) present in the groundwater at multilevel MW-302 in Ports 7 and 8 screened between 304.33 and 304.13 m AMSL and 303.33 and 303.13 m AMSL, respectively. Error bars denote typical seasonal fluctuations in measured concentrations of toluene attributed to the transient hydrogeological conditions that exist at the Site.

The dissolved BTEXTMB concentrations during the spring 2010 groundwater sampling program are within the pre-remediation range as illustrated in Figures 7.11 and 7.12. The historical variability between BTEXTMB measured in the dissolved phase was limited to two fall and two spring groundwater monitoring sessions pre-injection, where the groundwater level is at a seasonal low (fall) and high (spring). The remedial efforts did not significantly reduce the dissolved contaminants at the monitors that received the remedial solution. Considering the large amount of residuals present in the target area, contaminants in the dissolved phase plume that were removed through denitrification would readily be replenished through partitioning from the NAPL into the dissolved phase, thus observed differences in dissolved BTEXTMB post-injection are not anticipated.

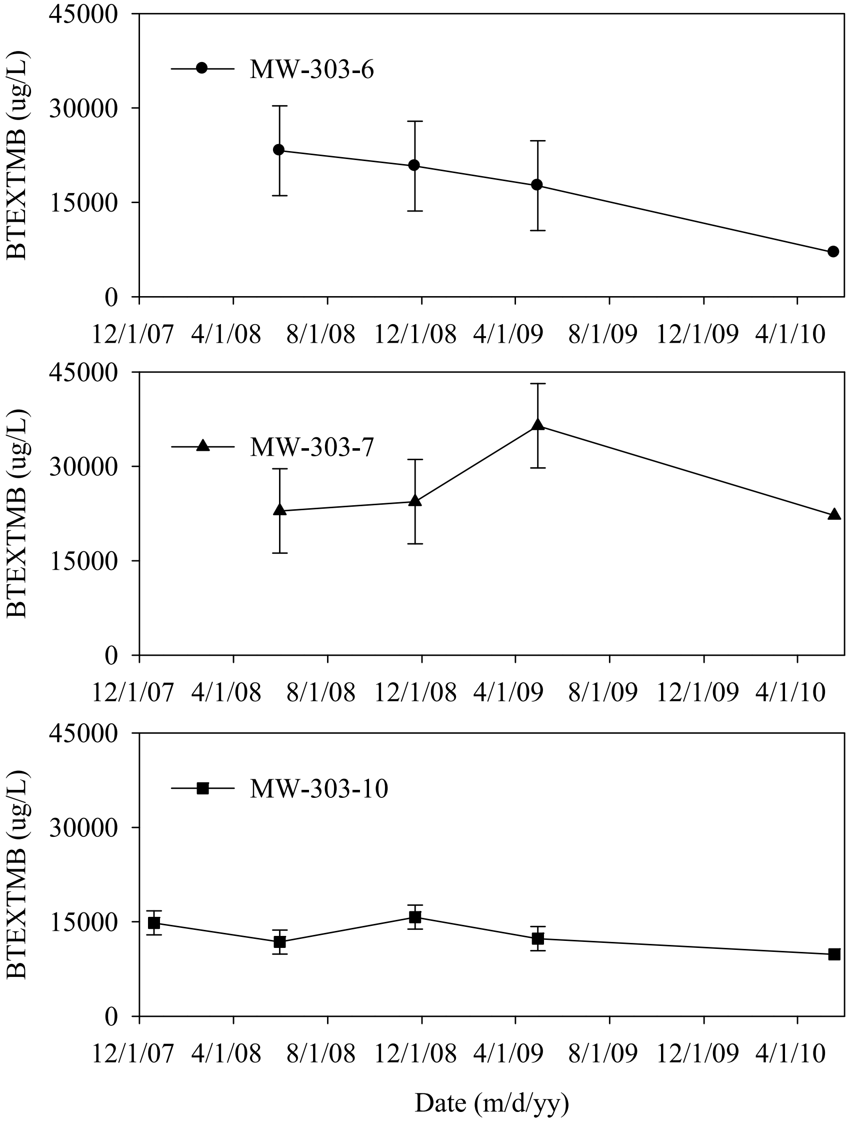

Figure 7.11: Post-injection BTEXTMB concentration in groundwater in non-treated treated zone at multilevel well MW-303 at ports 6, 7 and 10.

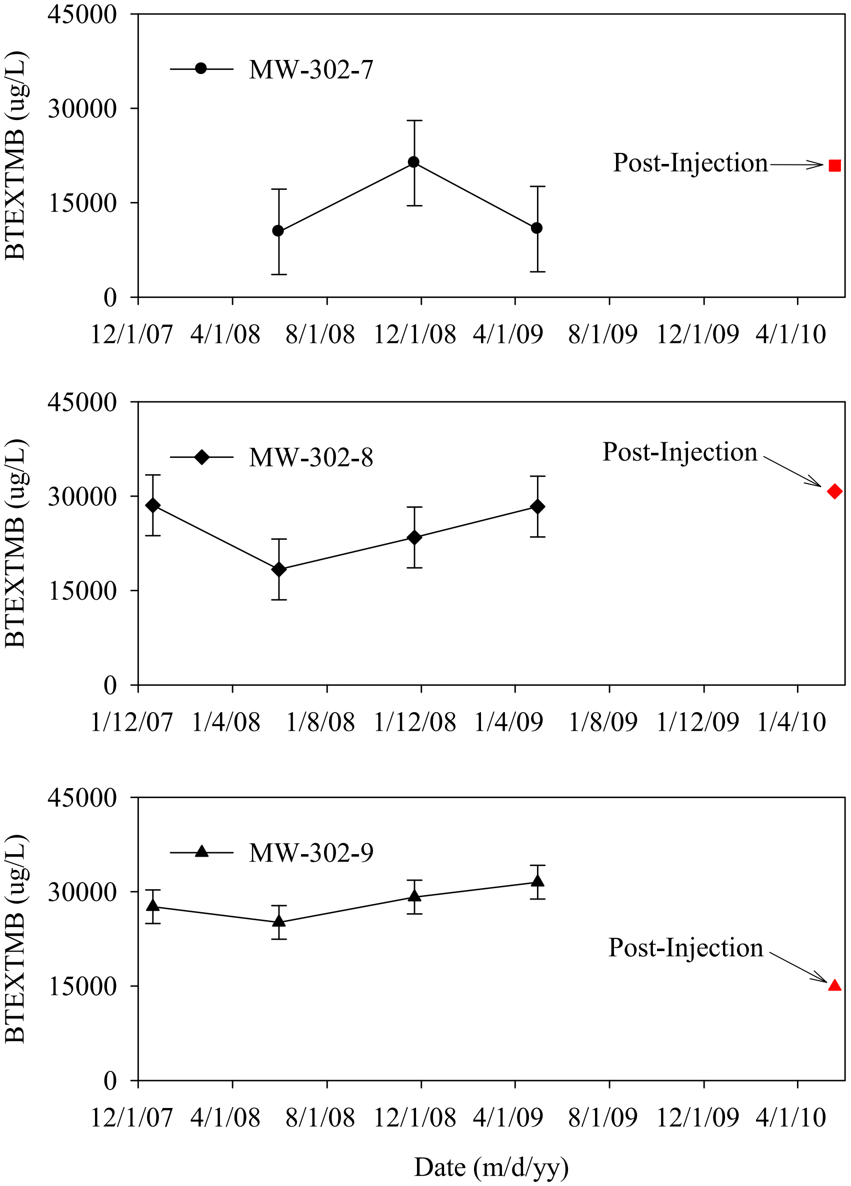

Figure 7.12: Post-injection BTEXTMB concentrations in groundwater in treated zone at multilevel well MW-302 at ports 7, 8 and 9, where remedial tracer solution was consistently recovered.

7.3.2 Results of Pre- and Post-Injection Soil Coring

The results of the pre-injection coring indicate that residual contaminants are present throughout the majority of the soil profile, at approximate elevations between 309 and 301 m AMSL. The delivery of the TEA amended remedial test solution was designed for the 305 and 303 m AMSL interval of the contaminated aquifer determined during the pre-injection coring in order to a target these maximum soil concentrations of BTEXTMB consistently observed at that elevation range within the study area.

Post-injection core was collected by B. Katanchi in October 2009 at four locations in Row 2, situated approximately 3.7 m downgradient of the injection well. Boreholes BH-601, BH-602, BH-603 and BH-604 were drilled in Row 2, parallel to the upgradient and downgradient multilevel groundwater monitors situated in Row 1 and Row 3, respectively. Soil samples were collected at discrete intervals following the procedure described in Appendix B and analyzed for gasoline constituents BTEXTMB. The remediation efforts were designed to target aquifer materials containing residual contamination.

Post-injection core samples were analyzed for BTEXTMB compounds and the results are summarized in Appendix F. The post-injection vertical distribution of toluene is presented in Figure 7.13 for simplicity and the distribution was generally in agreement with BTEXTMB. Similar to what was observed during the pre-injection investigations carried out in rows 1 and 3; peak concentrations of contaminants were measured between 303 and 305 m AMSL. Figure 7.14 depicts the vertical and spatial distribution of toluene in borehole locations BH-303, BH-601, BH-304 and BH-406 situated in Row 1, 2 and 3 respectively and beyond the influence of the remedial test solution where no effects in any case were expected. The results of the pre- and post-injection coring activities presented in Figure 7.14 are consistent with each other indicating that the loss of petroleum hydrocarbons in relation to the amount of measured denitrification is too small to detect.

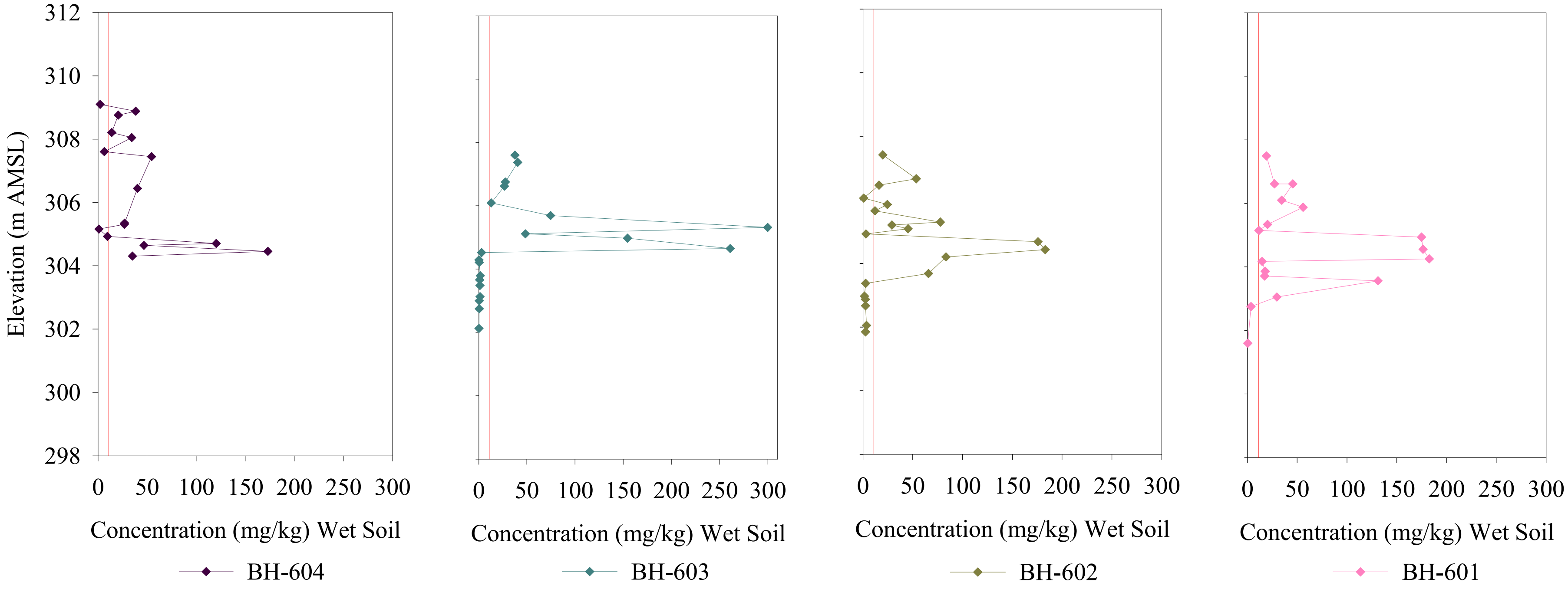

Figure 7.13: Post- remedial vertical distribution of toluene (mg/kg) wet soil extraction concentrations at the borehole locations of the 600 series monitoring wells from north to south (BH-604, BH-603, BH-602 and BH-601) in Row 2 retrieved in October 2009 following the delivery of remedial solution to targeted areas of the contaminated aquifer. Vertical red line denotes residual NAPL inferred at total extraction concentrations exceeding 13 mg/kg wet soil.

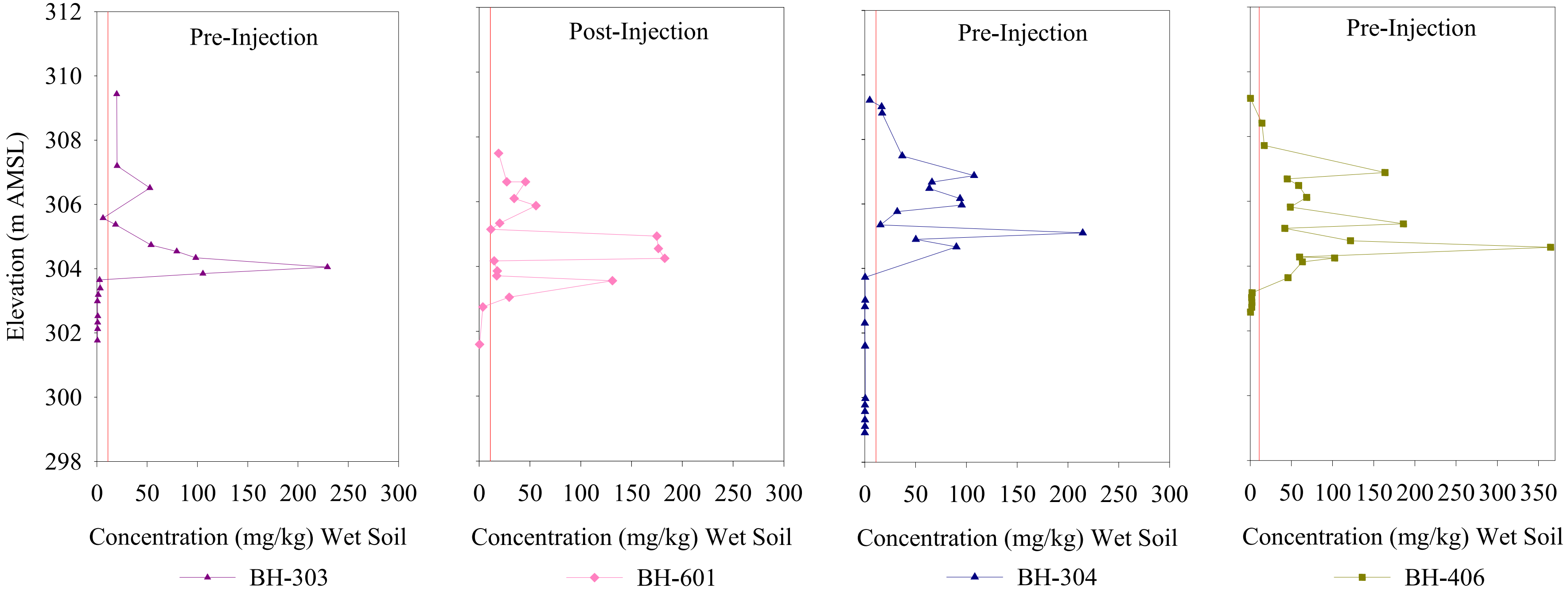

Figure 7.14: Toluene (mg/kg) wet soil concentrations, where BH-303, BH-304 and BH-406 were retrieved pre- injection of remedial solution and BH-601 was retrieved post-injection.

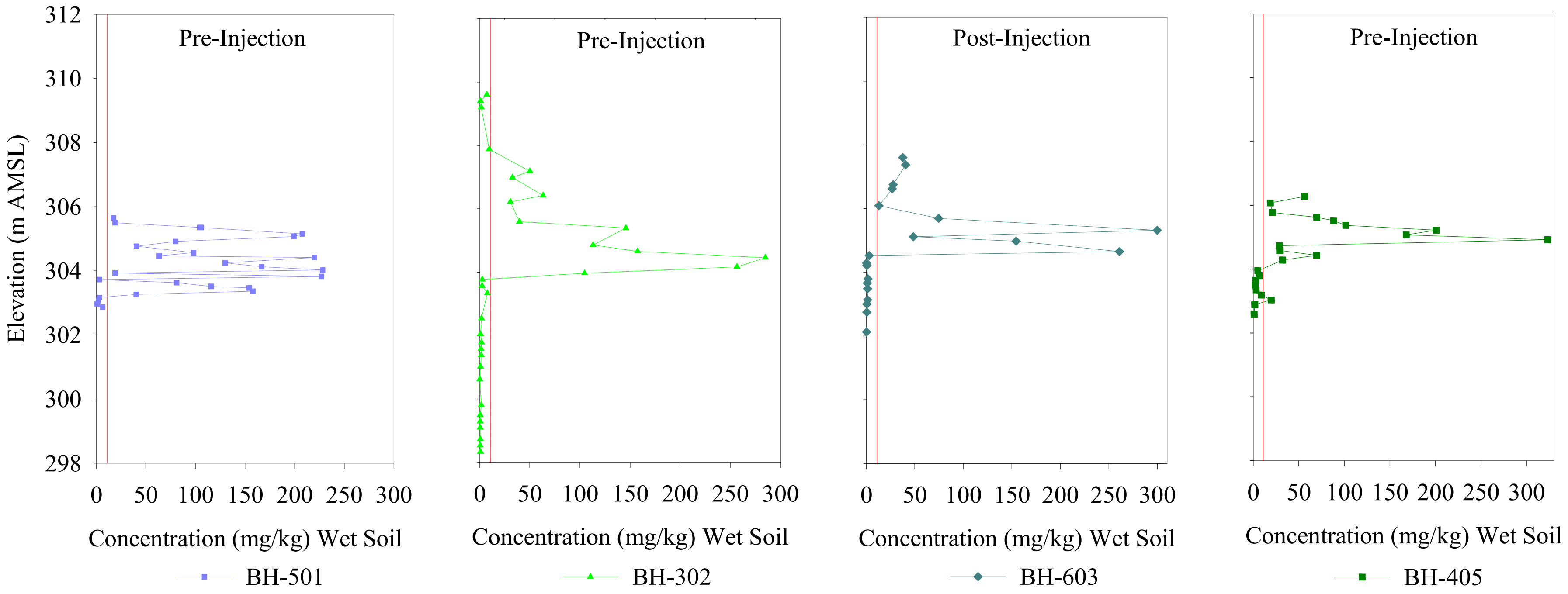

Figure 7.15: Pre- and post-injection measurement of toluene concentrations (mg/kg) wet soil, where BH-501, BH-302 and BH-405 were retrieved prior to injection of remedial solution to areas of the aquifer containing residual contaminants.

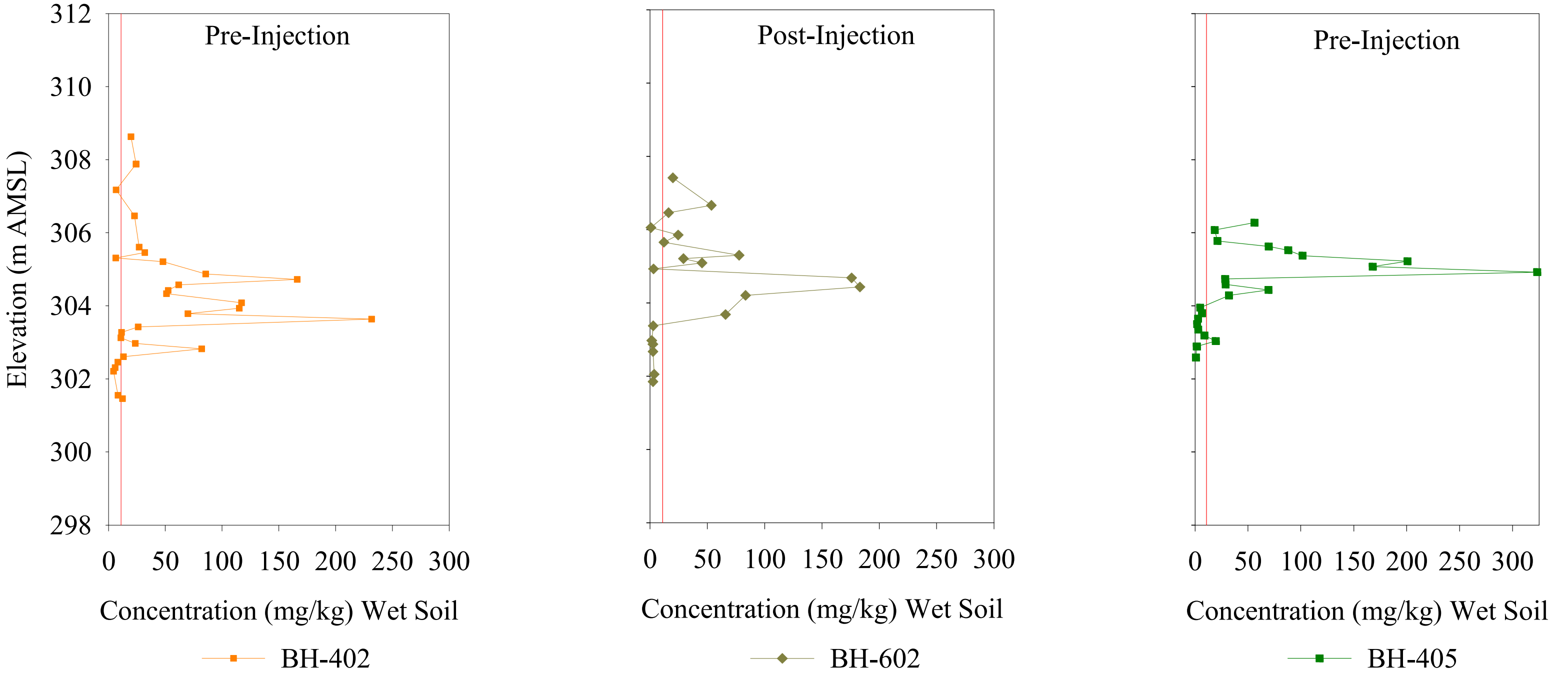

Figure 7.16: Pre- and post-injection measurement of toluene concentrations (mg/kg) wet soil, where BH-402 and BH-405 were retrieved prior to injection of remedial solution to areas of the aquifer containing residual contaminants.

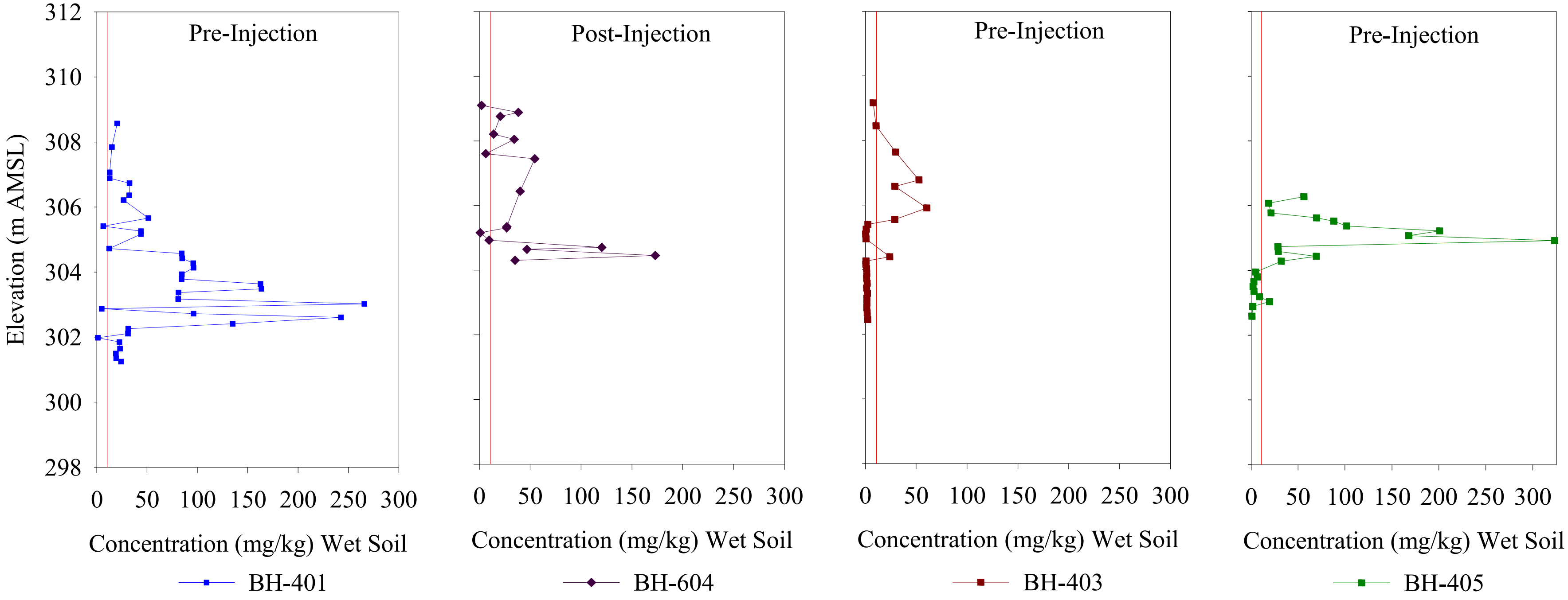

Figure 7.17: Pre- and post-injection measurement of toluene concentrations (mg/kg) wet soil, where BH-401, BH-403 and BH-405 were retrieved prior to injection of remedial solution to areas of the aquifer containing residual contaminants.

Using the Feenstra et al. (1991) rationale discussed in Chapter 3, residuals are inferred when the total soil extract concentration of BTEXTMB compounds exceed 13 mg/kg wet soil and NAPL is potentially mobile at BTEXTMB concentrations exceeding 3,000 mg/kg. The vertical distribution of toluene in regions of the study area subject to the delivery of the remedial test solution is presented in Figures 7.15, 7.16 and 7.17. A continuous plume of TEA amended water was well documented between MW-501 and Row 1, however only limited quantities of Br^- tracer were recovered in Row 2 (MW-602 and MW-603) and Row 3 (MW-405, only). The overall content of target aromatic hydrocarbons in regions of the aquifer containing residual NAPL was not reduced by the remedial injections, which is a reflection of the limited amount of nitrate delivered to the target residual zone compared to the large contaminant mass present.

The results of the vertical distribution of BTEXTMB and in particular toluene following the delivery of a continuous supply of TEA to the target zone are consistent with the pre-injection investigation results. The vertical distribution of toluene is variable; however there is the same concentrated area of contaminants at the interval 305 to 303 m AMSL that was measured during pre-injection coring. Contaminant mass removal must have occurred as Br^- tracer evidence indicates that NO_3^- was utilized in the study area based on the inference of denitrification rates. However, the post-injection soil core results are unable to demonstrate the reduction in individual toluene, let alone BTEXTMB hydrocarbon levels, reflecting the limited nitrate provided relative to the significant but heterogeneously distributed residual mass in the target zone.

Chapter 8: Conclusions and Recommendations

The nitrate-amended remedial solution was successfully delivered to the target zone of the anaerobic aquifer containing residual hydrocarbons. A plume of remedial solution was established within the remedial monitoring network, following consecutive pulsed injections of remedial solutions where Br^- tracer concentrations were eventually equivalent to greater than 50% of the concentration injected. Denitrification in the study area was induced by the addition of nitrate reactant in the form of sodium nitrate ($NaNO_3$) in concentrations ranging between 90 and 265 mg/L NO_3^- while residual and dissolved hydrocarbon contaminants present in the aquifer served as the carbon source. The concentration of nitrate within the remedial solution was increased over time as the microbes had the opportunity to acclimate to the TEA enriched conditions and groundwater quality monitoring from downgradient wells revealed that nitrate was being readily attenuated. Post-injection groundwater monitoring revealed that nitrate and nitrite concentrations were well below the ODWQS of 10 mg/L as total nitrogen despite elevated concentrations used in the injections.

A continuous zone of remedial test solution amended with TEA developed as a result of the consecutive series of pulsed injections delivered via the injection well, thereby providing a sustainable supply of TEA to promote in situ biodegradation of petroleum contaminants. Background concentrations of Br^- within the monitoring network increased during the series of injections, as the amended treatment water was more prone to mixing with the remaining remedial plume situated in the vicinity of the injection well.

The results of the Br^- tracer breakthrough curves indicate that different preferential flow pathways were established under the transient saturated conditions present at the Site, although the behaviour of the injected remedial slug was generally consistent between the different units and the test solution was ultimately delivered to the target zone. The injectate primarily moved in the high K zone of Unit 3 under high saturated conditions, which eventually became unsaturated due to seasonal declines of the groundwater level. The lower portion of Unit 4 comprised of higher permeable materials was able to transmit the test solution more effectively under low seasonal groundwater levels.

It is clear that the delivery of the remedial test solution upon injection is influenced by the heterogeneous characteristics of the aquifer materials and the transient hydrogeological conditions present at the Site. Upon the return to natural gradient conditions, the injected remedial slug was transported through the aquifer at velocities characterized by the porous media and the hydraulic conditions. In general, the remedial solution was transported more rapidly under high groundwater elevations and gradients, where maximum velocities corresponding to Unit 2, 3 and 4 of 1.91, 1.00 and 0.76 m/day respectively were observed. Under low groundwater elevations and gradient, the remedial solution was not transported in Unit 2 because it was no longer saturated, while minimum velocities were observed in Unit 3 and Unit 4, 0.06 and 0.04 m/day. Groundwater velocities estimated from the removal of Br^- tracer within the injection well were less than 0.01 m/day under the reduced hydrogeological conditions observed during the November injections. The remedial solutes were transported in sand and gravel Unit 5 at an approximate rate of 0.10 m/day, estimated from the arrival of the Br^- tracer at Row 3, 62 days after the first injection.

A cumulative mass of 3.7 kg of nitrate was added to the target aquifer during the course of the remedial injections. Evidence demonstrating NO_3^- was used a terminal electron acceptor in the bioremediation of the petroleum-contaminated aquifer include: 1) laboratory confirmation of the indigenous microbial population’s capability to degrade hydrocarbons using nitrate as the TEA, 2) decrease of nitrate relative to a conservative Br^- tracer, 3) generation of nitrite, an intermediate in denitrification and 4) reduction in dissolved phase toluene.

Soil coring and groundwater sampling was conducted downgradient from the injection source zone in order to assess measured changes in quantities of toluene in each respective medium by enhancing in-situ bioremediation of petroleum hydrocarbons at the Site with the addition of nitrate as a terminal electron acceptor. Pre-treatment measured peak concentrations of BTEXTMB in the groundwater (40 mg/L) and soil (2,700 mg/kg wet soil) were significantly higher than the maximum concentration of nitrate in the remedial test solution (265 mg/L NO_3^-). However, the results of the post-injection coring indicate insufficient quantities of nitrate were added to the system in order to induce a clear decline in residual toluene or BTEXTMB concentrations.

Given the variable hydrogeological conditions present at the Site influenced by seasonal effects, the delivery of the remedial solution to target zones containing petroleum hydrocarbons at residual saturation is more effective under lower gradient, low water-table conditions. The delivery of TEA amended water to enhance the in situ biodegradation of petroleum contaminants is more effective when the treatment water has an increased residence time in the target remedial zone, attributed to low gradients and groundwater transport velocities at the Site. Longer residence periods enable the indigenous microbes to have increased contact time with the TEA which will be preferentially utilized to degrade the contaminants.

Nitrate enhanced in situ bioremediation has been successfully demonstrated at a petroleum impacted aquifer, however a large scale application of the remedial strategy and long term monitoring would be required in order to evaluate the potential for measurable reductions in mass of contaminant emanating from the source zone. Based on the range of nitrate utilization rates inferred in situ (0.10 to 0.77 day^{-1}), it would take at onwards of 2 to 50+ years to remove the estimated 193 mol or 18 kg of toluene present in the subsurface based on weekly remedial solution injections (2.05 m^3, 265 mg/L NO_3^-) using a single injection well depending on the rate of nitrate utilization. The bioremediation timeframe could likely be reduced by increasing the number of injection wells or naturally with the use of utilization of alternative electron acceptors present in the subsurface.

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Appendix A

Well Construction Details, Boreholes and Information Supporting Site Characterization

Table A.1: Summary of monitoring network well details of SNC-Lavalin Inc. wells.

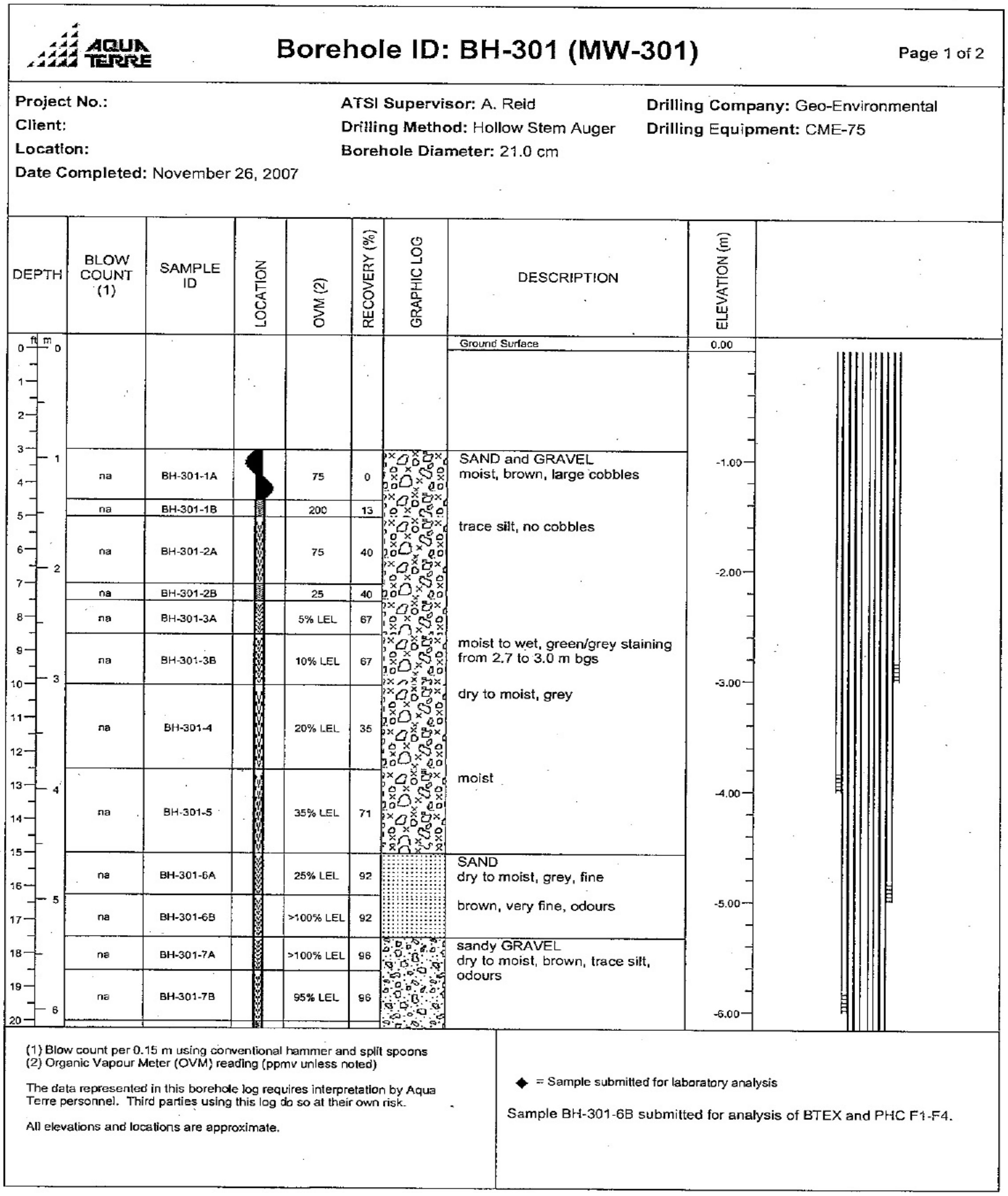
Well ID	Installation Date	Well Inner Diameter (m)	Screen length (m)	Well Screen Top (m bgs)	Well Screen Bottom (m bgs)	Ground Elevation (m AMSL)	Top Well Screen Elevation (m AMSL)	Bottom Well Screen (m AMSL)
MW-1	Mar-03-99	0.051	3.05	4.19	7.25	311.18	306.99	303.93
MW-3	Mar-04-99	0.051	3.05	4.4	7.45	311.43	307.03	303.98
MW-4	Mar-03-99	0.051	3.05	3.82	6.87	310.67	306.85	303.8
MW-5	Mar-02-99	0.051	3.05	2.89	7.94	311.2	308.31	303.26
MW-12	Mar-04-99	0.051	3.05	3.91	6.96	311.71	307.8	304.75
MW-101	May-14-01	0.102	6.09	1.33	7.43	311.25	309.92	303.82
MW-102	Nov-23-01	0.102	7.62	1.19	8.81	311.12	309.93	302.31
MW-103	Nov-22-01	0.102	7.62	0.54	8.16	311.33	310.79	303.17
MW-106	Nov-22-01	0.051	7.62	0.61	8.23	310.73	310.12	302.5
MW-107	Nov-21-01	0.051	7.62	0.23	7.85	311.01	310.78	303.16
MW-109	Nov-22-01	0.051	7.62	0.26	7.88	311.73	311.47	303.85
MW-201	Nov-11-02	0.051	7.62	1.4	9.02	310.1	308.7	301.08
MW-202	Nov-11-02	0.051	7.62	1.3	8.98	310.1	308.8	301.12
MW-203	Nov-11-02	0.051	7.62	1.3	8.92	310.81	309.51	301.89
MW-204	Nov-13-02	0.051	7.62	1.4	9.02	310.6	309.2	301.58
MW-205	Nov-13-02	0.051	7.62	1.4	9.02	310.06	308.66	301.04
MW-206	Nov-13-02	0.051	7.62	1.4	9.02	309.97	308.57	300.95

Table A.2: Summary of University of Waterloo monitoring well network well of 300, 400, 500 and 600 series wells.

Well ID	Installation Date	Well Inner Diameter (m)	Screen length (m)	Well Screen Top (m bgs)	Well Screen Bottom (m bgs)	Ground Elevation (m AMSL)	Top Well Screen Elevation (m AMSL)	Bottom Well Screen (m AMSL)
MW-301	Nov-26-07	0.006	0.2	2.8	11.91	311.4	308.6	299.4
MW-302	Nov-27-07	0.006	0.2	2.8	12.74	311.13	308.33	298.13
MW-303	Nov-27-07	0.006	0.2	2.3	11.11	311.11	308.81	299.81
MW-304	Nov-28-07	0.006	0.2	2.8	11.66	310.94	308.14	298.94
MW-401	Jul-13-09	0.013	0.5	5	9.5	311.04	306.04	301.54
MW-402	Jul-13-09	0.025	0.5	5	9.5	311.09	306.09	301.59
MW-403	Jul-15-09	0.051	0.5	5	9.5	310.94	305.94	301.44
MW-404	Jul-14-09	0.102	0.5	5	9.5	310.91	305.91	301.41
MW-405	Jul-14-09	0.203	0.5	5	9.5	310.91	305.91	301.41
MW-406	Jul-14-09	0.406	0.5	5	9.5	310.9	305.9	301.4
MW-501	Jul-15-09	0.813	2	6.21	8.21	311.19	304.99*	302.99*
MW-601	Oct-27-09	0.025	0.5	7.45	7.95	310.97	303.52	303.02
MW-602	Oct-28-09	0.025	0.5	8.03	8.53	310.93	302.9	302.4
MW-603	Oct-28-09	0.025	0.5	7.43	7.93	310.95	303.52	303.02
MW-604	Oct-29-09	0.025	0.5	6.84	7.34	310.95	304.11	303.61

* injection well MW-501 open interval is between 306 to 302.8 due total length of sand pack and well screen before bentonite seal.

SNC-Lavalin (ATSI) prepared boreholes for coring and installation of multilevel wells and an injection well between November 2007 and October 2009 for the University of Waterloo.



Borehole ID: BH-301 (MW-301)

Page 1 of 2

Project No.:
Client:
Location:
Date Completed: November 26, 2007

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m)
0							Ground Surface	0.00
	na	BH-301-1A	◆	75	0		SAND and GRAVEL moist, brown, large cobbles	-1.00
	na	BH-301-1B		200	13			
	na	BH-301-2A		75	40		trace silt, no cobbles	-2.00
	na	BH-301-2B		25	40			
	na	BH-301-3A		5% LEL	67			
	na	BH-301-3B		10% LEL	67		moist to wet, green/grey staining from 2.7 to 3.0 m bgs	-3.00
	na	BH-301-4		20% LEL	35		dry to moist, grey	
	na	BH-301-5		35% LEL	71		moist	-4.00
	na	BH-301-6A		25% LEL	92		SAND dry to moist, grey, fine	
	na	BH-301-6B		>100% LEL	92		brown, very fine, odours	-5.00
	na	BH-301-7A		>100% LEL	96		sandy GRAVEL dry to moist, brown, trace silt, odours	
20 ft / 6 m	na	BH-301-7B		95% LEL	96			-6.00

(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Sample BH-301-6B submitted for analysis of BTEX and PHC F1-F4.

Borehole ID: BH-301 (MW-301)

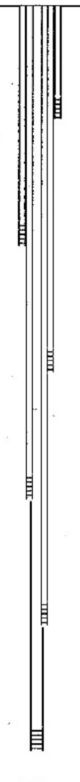
Page 2 of 2

Project No.: [redacted]
Client: [redacted]
Location:
Date Completed: November 26, 2007

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m)
21	na	BH-301-8A		40% LEL	83			
	na	BH-301-8B		100% LEL	83		sand seam from 6.5 to 6.7m bgs	
22	na	BH-301-8C		80% LEL	83			
23 7 24	na	BH-301-9	◆	>100% LEL	100		SAND wet, brown, fine, some silt. odours trace gravel	-7.00
25 26	na	BH-301-10A		45% LEL	100		no gravel	
8	na	BH-301-10B		>100% LEL	100		grey gravel seam from 8.1 to 8.2 m bgs	-8.00
27	na	BH-301-10C		5% LEL	100			
28 29 9 30	na	BH-301-11		25% LEL	100		trace gravel no gravel	-9.00
31	na	BH-301-12A		100% LEL	100		gravelly SAND moist to wet, brown, large cobbles present	
32	na	BH-301-12B		45% LEL	100			
10 33	na	BH-301-13A		30% LEL	100		brown/grey, no cobbles	-10.00
34	na	BH-301-13B		35% LEL	100			
35	na	BH-301-14A	◆	325	100			
36 11	na	BH-301-14B		200	100			-11.00
37	na	BH-301-14C		175	100		3 cm silt seam at 11.4 m bgs	
38 39 12 40	na	BH-301-15		375	33		large cobbles End of borehole at 12.2 m bgs	-12.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Samples BH-301-9 and BH-301-14A submitted for analysis of BTEX and PHC F1-F4.

AQUA TERRE

Borehole ID: BH-302 (MW-302)

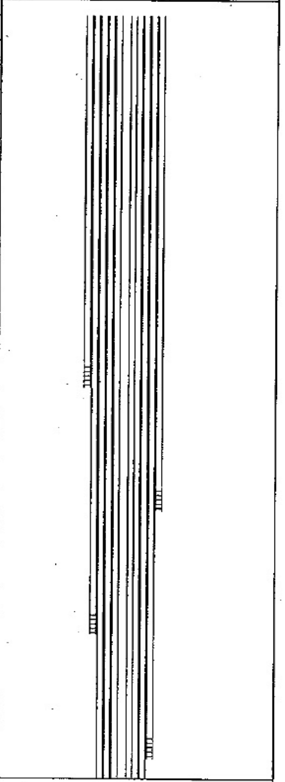
Page 1 of 3

Project No.:
Client:
Location:
Date Completed: November 27, 2007

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75

DEPTH (m)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m)
0							Ground Surface	0.00
1	na	BH-302-1A		<25	76		SAND and GRAVEL moist, brown, large cobbles grey, silty, no cobbles, odours	-1.00
	na	BH-302-1B		5% LEL	76			
2	na	BH-302-2		5% LEL	72			-2.00
3	na	BH-302-3		15% LEL	59			
	na	BH-302-4A		5% LEL	43			-3.00
	na	BH-302-4B		20% LEL	43			
4	na	BH-302-5		45% LEL	55		gravelly SAND moist, grey, trace silt, staining from 4.3 to 4.4 m bgs	-4.00
	na	BH-302-6A		30% LEL	55		SAND moist, grey, trace silt black staining, odours	
5	na	BH-302-6B	◆	40% LEL	55			-5.00
	na	BH-302-6C		50% LEL	55		SAND and GRAVEL dry to moist, brown/grey, some silt	
6	na	BH-302-7		90% LEL	87			-6.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Sample BH-302-6B submitted for analysis of BTEX and PHC F1-F4.

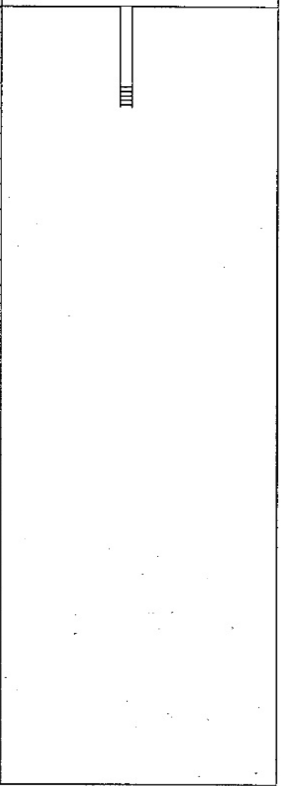
AQUA TERRE

Borehole ID: BH-302 (MW-302)

Page 3 of 3

Project No.:	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client:	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME-75
Location:	**Borehole Diameter:** 21.0 cm	
Date Completed: November 27, 2007		

DEPTH (ft)	DEPTH (m)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m)
41								SAND moist to wet, grey, trace gravel	
41–42		na	BH-302-16	◆	150	100		SAND and GRAVEL moist to wet, grey	
43–44	13	na	BH-302-17		75	48		GRAVEL wet, large cobbles	-13.00
44								End of borehole at 13.4 m bgs	
46	14								-14.00
49	15								-15.00
52–53	16								-16.00
56	17								-17.00
59	18								-18.00
60									



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Sample BH-302-16 submitted for analysis of BTEX and PHC F1-F4.

AQUA TERRE

Borehole ID: BH-303 (MW-303)

Page 1 of 2

Project No.:
Client:
Location:
Date Completed: November 27, 2007

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75

DEPTH (ft / m)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m)
0 / 0							Ground Surface	0.00
1, 2								
3, 4 / 1	na	BH-303-1A		25	83		SAND and GRAVEL dry to moist, brown, trace silt	-1.00
5	na	BH-303-1B		5% LEL	83		grey	
6, 7, 8, 9 / 2	na	BH-303-2		15% LEL	33		brown/grey, some silt	-2.00
10, 11, 12 / 3							No Recovery	-3.00
13, 14 / 4	na	BH-303-3		10% LEL	27		silty SAND and GRAVEL dry to moist, dark brown	-4.00
15, 16, 17 / 5	na	BH-303-4		15% LEL	7		moist, wood pieces present	-5.00
18	na	BH-303-5A		20% LEL	80		dry to moist, large cobbles	

(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

AQUA TERRE

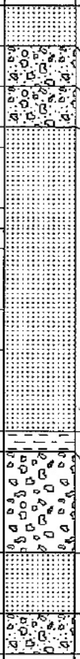
Borehole ID: BH-303 (MW-303)

Page 2 of 2

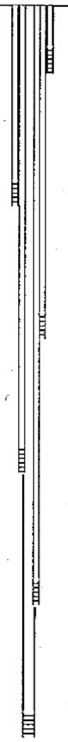
Project No.:
Client:
Location:
Date Completed: November 27, 2007

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75



DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m)
6	na	BH-303-5B	◆	>100% LEL	80		SAND dry to moist, brown, some gravel, some silt, some gravel	-6.00
20	na	BH-303-6A		50% LEL	100		sandy, silty GRAVEL dry to moist, grey/black staining	
21 22	na	BH-303-6B		35% LEL	100		SAND and GRAVEL dry to moist, brown, trace silt	
	na	BH-303-6C		>100% LEL	100		SAND wet, brown, staining, odours 4 cm silt seam at 7.4 m bgs	
23 7	na	BH-303-7A		>100% LEL	100			-7.00
24	na	BH-303-7B		125	100		grey, medium	
25	na	BH-303-7C		150	100		trace gravel	
26 8	na	BH-303-8A		5% LEL	80			-8.00
27	na	BH-303-8B		225	80		grey, fine to medium, staining	
28 29	na	BH-303-9A	◆	5% LEL	100			
9	na	BH-303-9B		100	100		SILT moist, brown, large cobbles	-9.00
30 31 32	na	BH-303-10		75	40		GRAVEL moist, grey, trace sand, odours present	
10 33	na	BH-303-11A	◆	200	36		SAND wet, brown, large cobbles	-10.00
34	na	BH-303-11B		75	36		SAND and GRAVEL wet, brown/grey	
35 36 11 37							No Recovery	-11.00



(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Samples BH-303-5B, BH-303-9A & BH-303-11A submitted for analysis of BTEX and PHC F1-F4.

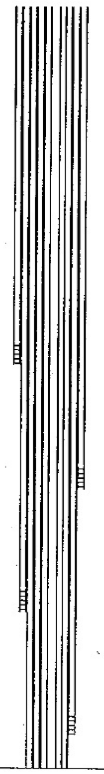
AQUA TERRE

Borehole ID: BH-304 (MW-304)

Page 1 of 2

Project No.:	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client:	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME-75
Location:	**Borehole Diameter:** 21.0 cm	
Date Completed: November 27, 2007		

DEPTH (ft / m)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m)
0 / 0							Ground Surface	0.00
3–5 / 1	na (sampled from augers)	BH-304-1		<25	61		SAND and GRAVEL moist, light brown, trace silt, large cobbles	-1.00
5–7.5 / 2							No Sample	-2.00
8	na	BH-304-2A		5% LEL	100		SAND and GRAVEL moist, dark brown	
9	na	BH-304-2B	◆	10% LEL	100		SAND moist, green/black staining	
10 / 3	na	BH-304-2C		10% LEL	100			-3.00
11–12	na	BH-304-3	◆	20% LEL	69		SAND and GRAVEL moist, light brown, some silt	
13 / 4	na	BH-304-4A		70% LEL	100		SAND dry to moist, brown, fine	-4.00
14	na	BH-304-4B		15% LEL	100		SAND and GRAVEL dry to moist, brown, coarse, some silt	
16 / 5	na	BH-304-5		50% LEL	100			-5.00
18	na	BH-304-6A	◆	55% LEL	100			
19–20 / 6	na	BH-304-6B		>100% LEL	100		SAND moist, brown/grey, fine, black staining from 5.9 to 6.0 m bgs	-6.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Sample BH-304-2B submitted for analysis of pH.
Samples BH-304-3 submitted for analysis of BTEX and PHC F1-F4.
Sample BH-303-6A submitted for analysis of BTEX, PHC F1-F4 & pH.

Borehole ID: BH-304 (MW-304)

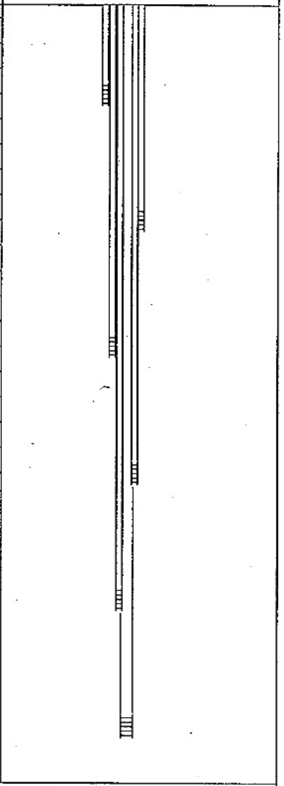
Page 2 of 2

Project No.:
Client:
Location:
Date Completed: November 27, 2007

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m)
	na	BH-304-7A		>100% LEL	100			
21 22	na	BH-304-7B		40% LEL	100		sandy GRAVEL moist,brown/grey, large cobbles	
23 — 7 24 25	na	BH-304-8		20% LEL	72		wet	-7.00
26 — 8 27	na	BH-304-9		25	100			-8.00
28 29 — 9 30	na	BH-304-10		50	81		sandy, silty, GRAVEL wet, brown,	-9.00
31 32	na	BH-304-11	◆	200	100		gravelly SAND wet, brown, large cobbles	
33 — 10 34 35	na	BH-304-12		125	27		SAND and GRAVEL wet, brown/grey	-10.00
36 — 11 37	na	BH-304-13		200	65		SAND wet, brown/grey	-11.00
38	na	BH-304-14A		175	100			
39	na	BH-304-14B		125	100		silty SAND and GRAVEL moist to wet, light brown	
— 12 40							End of borehole at 11.9 m bgs	-12.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Sample BH-304-11 submitted for analysis of BTEX and PHC F1-F4.

Borehole/Monitoring Well ID: BH-401 (MW-401)

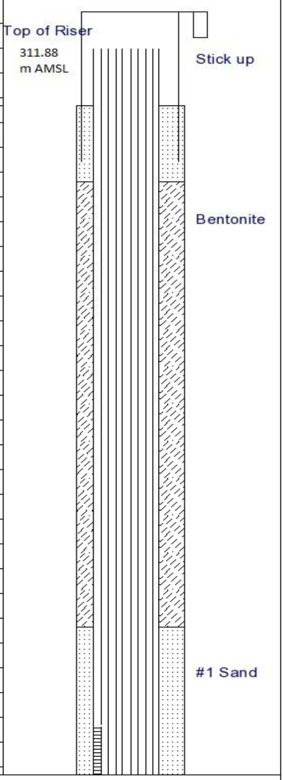
Page 1 of 2

Project No.:
Client:
Location:
Date Completed: July 13, 2009
Site Datum:

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter:

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75
Well Casing: Stick Up
Well Screen: U of W Multi-level

DEPTH (ft)	DEPTH (m)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m AMSL)
-2 -1									
0								Ground Surface	311.04
1 2 3 4	1							Not sampled	310.00
5 6 7	2	na	BH-401-1		5% LEL	11		SAND and GRAVEL moist, brown, some silt, cobbles, odours	309.00
8 9		na	BH-401-2		40% LEL	51		silty, grey staining	
10 11 12	3	na	BH-401-3		30% LEL	40		moist to wet, dark grey shiny staining	308.00
13	4	na	BH-401-4A		60% LEL	69		gravelly SAND wet, brown/grey, coarse, odours, black staining at 3.8 m bgs	307.00
14		na	BH-401-4B		60% LEL	69		brown, trace silt, cobbles	
15 16		na	BH-401-5A		>100% LEL	44		SAND moist to wet, brown/grey, fine, odours	306.00
17	5	na	BH-401-5B		>100% LEL	44		gravelly SAND wet, brown/grey, coarse, odours	



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

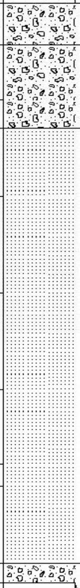
All elevations and locations are approximate.

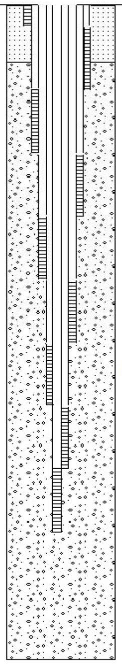
◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-401 (MW-401)

Page 2 of 2

Project No.:	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client:	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME-75
Location:	**Borehole Diameter:** 21.0 cm	**Well Casing:** Stick Up
Date Completed: July 13, 2009	**Monitoring Well Diameter:**	**Well Screen:** U of W Multi-level
Site Datum:		

DEPTH (ft)	DEPTH (m)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m AMSL)
18		na	BH-401-6A		>100% LEL	87		grey, medium to coarse, cobbles	
19	6	na	BH-401-6B		>100% LEL	87		SAND and GRAVEL wet, brown/grey, silty, odours, some staining on silty parts	305.00
20		na	BH-401-7A		>100% LEL	100		grey, no silt, coarse	
21 22		na	BH-401-7B		>100% LEL	100		SAND moist to wet, brown, fine, odours	
23 24	7	na	BH-401-8		>100% LEL	100		very fine from 6.8 to 6.9 m bgs wet, fine to medium	304.00
25 26 27	8	na	BH-401-9		>100% LEL	100		grey, fine	303.00
28 29		na	BH-401-10A		35% LEL	100		fine to medium	302.00
	9	na	BH-401-10B		250	100		brown/grey, trace silt, faint odours	
30 31		na	BH-401-11A		35% LEL	100		no silt, odours	
32		na	BH-301-11		5% LEL	100		gravelly SAND wet, brown/grey, medium to coarse, trace silt, cobbles	
33 34	10								301.00
35								End of borehole at 10.5 m bgs	
36 37	11								300.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-402 (MW-402)

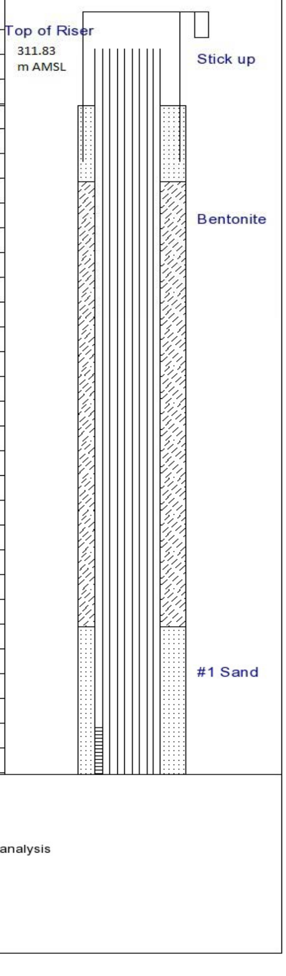
Page 1 of 2

Project No.:
Client:
Location:
Date Completed: July 13, 2009
Site Datum:

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter:

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75
Well Casing: Stick Up
Well Screen: U of W Multi-level

DEPTH (ft / m)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m AMSL)
-2 -1 0							Ground Surface	
1 2 3 — 1 4							Not sampled	310.00
5 6 — 2 7	na	BH-402-1		20% LEL	5		silty SAND dry to moist, brown, cobbles, odours	309.00
8 9	na	BH-402-2		35% LEL	51		silty SAND and GRAVEL moist, grey, cobbles, odours, grey staining	
10 — 3 11 12	na	BH-402-3		20% LEL	44			308.00
13 — 4 14	na	BH-402-4		10% LEL	27		less sand, dark grey shiny staining	307.00
15 16 — 5 17	na	BH-402-5		70% LEL	24		SAND and GRAVEL wet, grey, cobbles, odours, black staining	306.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-402 (MW-402)

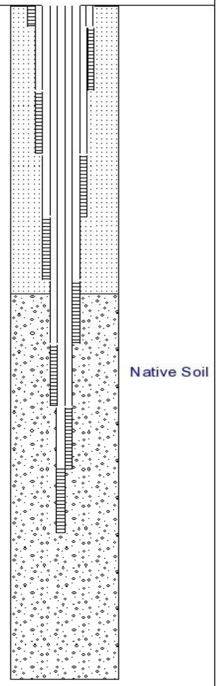
Page 2 of 2

Project No.:
Client:
Location:
Date Completed: July 13, 2009
Site Datum:

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter:

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75
Well Casing: Stick Up
Well Screen: U of W Multi-level

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m)
18	na	BH-402-6A		35% LEL	79			
19	na	BH-402-6B		65% LEL	79		brown, medium	
20 6	na	BH-402-6C		>100% LEL	79		moist to wet, fine, bands of black staining	305.00
	na	BH-402-7A		>100% LEL	100		wet, grey, no staining	
21 22	na	BH-402-7B		>100% LEL	100		moist, brown, fine to medium, bands of black staining	
23 7 24	na	BH-402-8		>100% LEL	100		SAND moist to wet, brown, fine to medium, some gravel from 7.3 m to 7.4 m bgs, odours	304.00
25 26 8	na	BH-402-9A		>100% LEL	100			303.00
27	na	BH-402-9B		>100% LEL	100		fine	
28	na	BH-402-10A		10% LEL	73		moist	
29 9	na	BH-402-10B		30% LEL	73		moist to wet	302.00
30 31 32	na	BH-402-11		60% LEL	69		brown/grey medium	
33 10 34 35								301.00
36 11 37							End of borehole at 10.7 m bgs	300.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

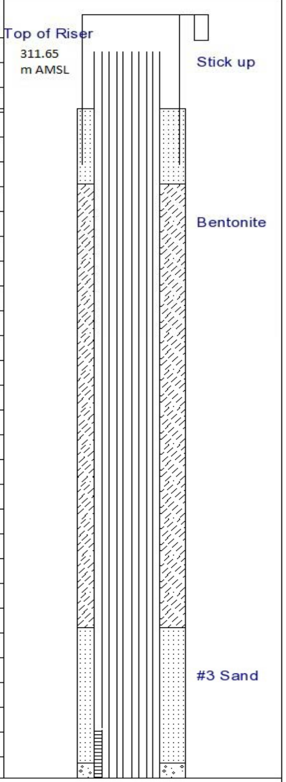
◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-403 (MW-403)

Page 1 of 2

Project No.:	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client:	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME-75
Location:	**Borehole Diameter:** 21.0 cm	**Well Casing:** Stick Up
Date Completed: July 15, 2009	**Monitoring Well Diameter:**	**Well Screen:** U of W Multi-level
Site Datum:		

DEPTH (ft / m)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION m AMSL
							Ground Surface	310.94
							Not sampled	310.00
	na	BH-403-1		50% LEL	67		silty SAND and GRAVEL moist, dark brown, odours	309.00
	na	BH-403-2		15% LEL	64		cobbles	308.00
	na	BH-403-3A		40% LEL	71		wood pieces	
	na	BH-403-3B		55% LEL	71		SAND moist, light brown/grey, fine, some gravel, trace silt, cobbles	
	na	BH-403-4A		35% LEL	87		brown/grey	307.00
	na	BH-403-4B		85% LEL	87		moist to wet, medium, fine sand from 4.3 m to 4.4 m bgs	
	na	BH-403-5A		>100% LEL	100		SAND and GRAVEL wet, brown, some silt, cobbles, odours, black staining	306.00
	na	BH-403-5B		>100% LEL	100			



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-403 (MW-403)

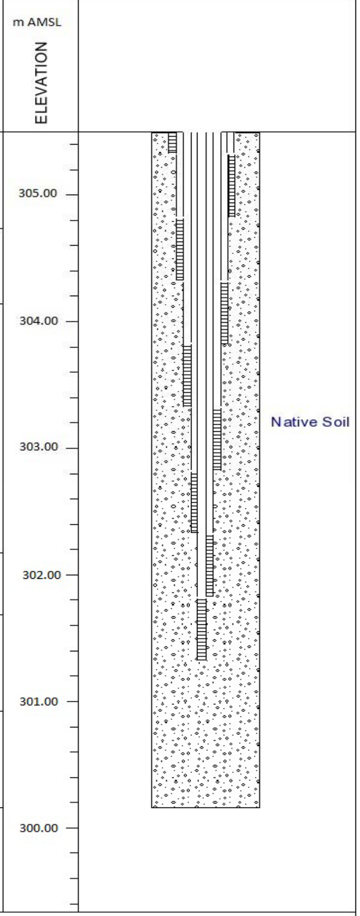
Page 2 of 2

Project No.:
Client:
Location:
Date Completed: July 15, 2009
Site Datum:

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter:

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75
Well Casing: Stick Up
Well Screen: U of W Multi-level

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION
18 19 6	na	BH-403-6		70% LEL	100		SAND moist to wet, brown, fine to medium
20 21	na	BH-403-7A		375	100		sandy GRAVEL wet, grey, cobbles, odours
22	na	BH-403-7B		250	100		SAND wet, brown, fine
23 7 24	na	BH-403-8		5% LEL	100		
25 26 8 27	na	BH-403-9		5% LEL	100		moist to wet, faint odours
28	na	BH-403-10A		5% LEL	100		wet, brown/grey, medium to coarse
29 9	na	BH-403-10B		425	100		sandy GRAVEL wet, grey, trace silt, cobbles
30 31 32	na	BH-403-11		375	100		gravelly SAND wet, grey, medium to coarse, cobbles
33 10 34							
35 36 11 37							End of borehole at 10.7 m bgs



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-404 (MW-404)

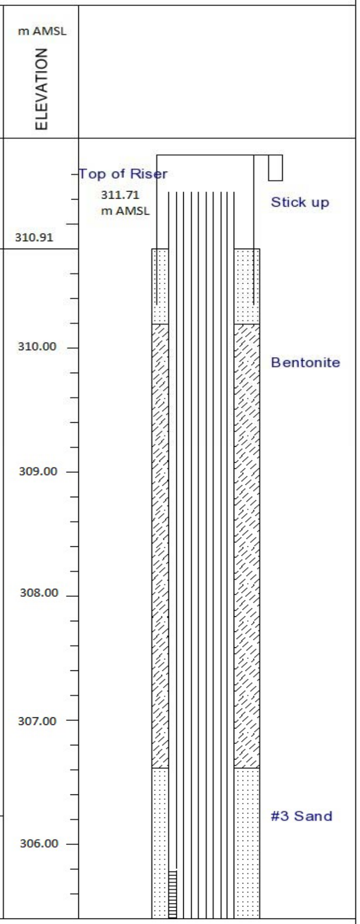
Page 1 of 2

Project No.:
Client:
Location:
Date Completed: July 14, 2009
Site Datum:

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter:

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75
Well Casing: Stick Up
Well Screen: U of W Multi-level

DEPTH (ft)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION
0							Ground Surface
0							Not sampled
15							No recovery - cobble stuck ahead of augers in ground



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

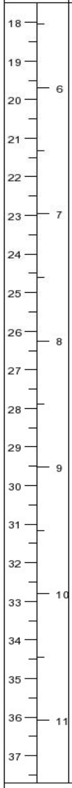
◆ = Sample submitted for laboratory analysis

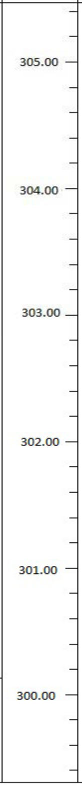
Borehole/Monitoring Well ID: BH-404 (MW-404)

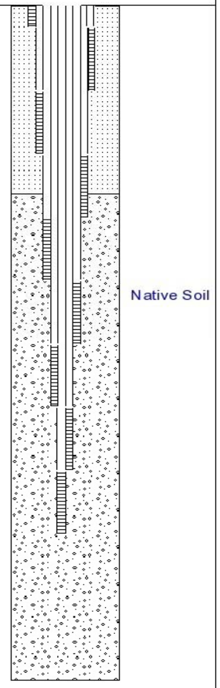
Page 2 of 2

Project No.:	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client:	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME-75
Location:	**Borehole Diameter:** 21.0 cm	**Well Casing:** Stick Up
Date Completed: July 14, 2009	**Monitoring Well Diameter:**	**Well Screen:** U of W Multi-level
Site Datum:		

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	m AMSL ELEVATION	
							End of borehole at 10.7 m bgs		







(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

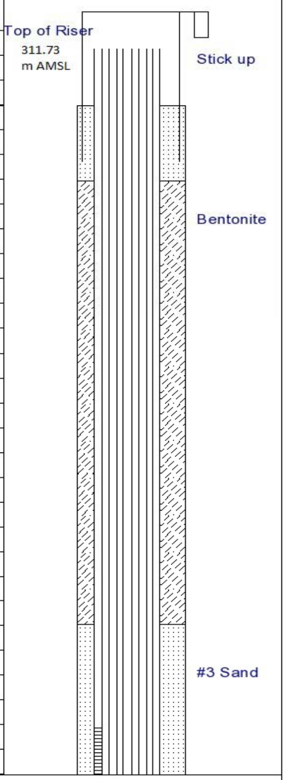
◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-405 (MW-405)

Page 1 of 2

Project No	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client:	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME-75
Location:	**Borehole Diameter:** 21.0 cm	**Well Casing:** Stick Up
Date Completed: July 14, 2009	**Monitoring Well Diameter:**	**Well Screen:** U of W Multi-level
Site Datum:		

DEPTH (ft / m)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m AMSL)
-2 -1								
0							Ground Surface	310.91
1 … 15 / 1 … 4							Not sampled	310.00 309.00 308.00 307.00
15	na	BH-405-1A	▓	70% LEL	100	░	gravelly SAND moist to wet, brown, medium	306.00
16 / 5	na	BH-405-1B	▓	95% LEL	100	░	wet, grey, medium to coarse	
17	na	BH-405-1C	▓	>100% LEL	100	░		



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

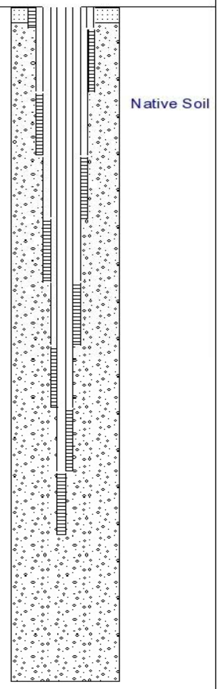
◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-405 (MW-405)

Page 2 of 2

Project No.:	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client.	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME-75
Location:	**Borehole Diameter:** 21.0 cm	**Well Casing:** Stick Up
Date Completed: July 14, 2009	**Monitoring Well Diameter:**	**Well Screen:** U of W Multi-level
Site Datum:		

DEPTH (ft)	DEPTH (m)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m AMSL)
18		na	BH-405-2A		>100% LEL	100		SAND wet, brown, medium to coarse, trace gravel, cobbles, odours	
19	6	na	BH-405-2B		>100% LEL	100		fine to very fine	305.00
20 21		na	BH-405-3A		>100% LEL	83		some gravel, bands of black staining	
22		na	BH-405-3B		25% LEL	83		sandy GRAVEL moist, brown, some silt, odours	304.00
23 24	7	na	BH-405-4		10% LEL	100		SAND moist to wet, brown/grey, medium to coarse, trace gravel, cobbles, odours, 5 cm band of fine sand at 7.6 m bgs	
25 26		na	BH-405-5A		35% LEL	100		some gravel	303.00
	8	na	BH-405-5B		5% LEL	100		brown, fine, trace gravel	
27		na	BH-405-5C		250	100		sandy GRAVEL brown/grey, some silt, cobbles, odours	
28		na	BH-405-6A		5% LEL	100		SAND wet, brown, medium to coarse, faint odours	
29	9	na	BH-405-6B		125	100		silty SAND and GRAVEL moist to wet, brown, cobbles	302.00
30 31 32 33 34 35	10								301.00
36 37	11							End of borehole at 10.7 m bgs	300.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

AQUA TERRE

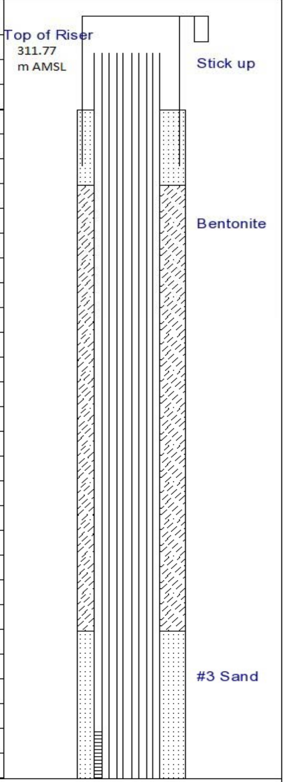
Borehole/Monitoring Well ID: BH-406 (MW-406)

Page 1 of 2

Project No.:	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client:	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME-75
Location:	**Borehole Diameter:** 21.0 cm	**Well Casing:** Stick Up
Date Completed: July 14, 2009	**Monitoring Well Diameter:**	**Well Screen:** U of W Multi-level
Site Datum:		

DEPTH (ft / m): ft -2, -1, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17; m 1, 2, 3, 4, 5

BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m AMSL)
						Ground Surface	310.90
						Not sampled	310.00
na	BH-406-1		5% LEL	55		SAND and GRAVEL moist, brown/ grey, silty, fine, cobbles, odours, grey staining	309.00
na	BH-406-2		30% LEL	52		medium to coarse, no silt, no staining	308.00
na	BH-406-3		25% LEL	35		moist	307.00
na	BH-406-4A		>100% LEL	88		SAND moist, brown, fine to very fine, trace silt	
na	BH-406-4B		90% LEL	88		SAND and GRAVEL wet, grey, medium to coarse, odours, yellow/gold residual product at 4.1 m bgs (below very fine sand)	
na	BH-406-5		60% LEL	89		trace silt, no staining	306.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-406 (MW-406)

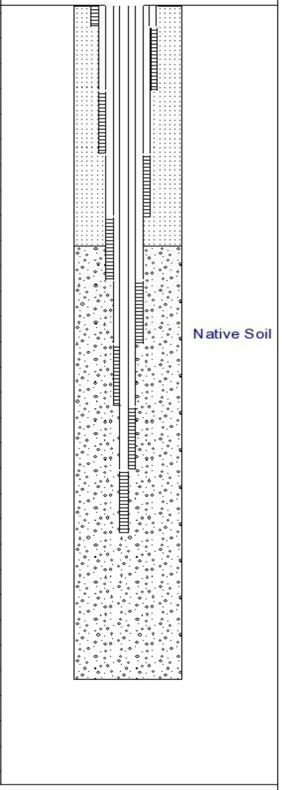
Page 2 of 2

Project No.:
Client:
Location:
Date Completed: July 14, 2009
Site Datum:

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter:

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75
Well Casing: Stick Up
Well Screen: U of W Multi-level

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	m AMSL ELEVATION
18	na	BH-406-6A		50% LEL	64		hard packed silt at 5.7 m bgs	
19 6	na	BH-406-6B		>100% LEL	64		SAND moist to wet, brown, fine, odours, bands of black staining at 6.1 m bgs	305.00
20 21	na	BH-406-7A		>100% LEL	100		fine to medium, trace gravel, fine sand at 6.6 m bgs	
22	na	BH-406-7B		90% LEL	100		sandy GRAVEL moist, brown/grey, coarse, some silt, odours, shiny black staining at 6.7 m bgs	304.00
23 7 24	na	BH-406-8		>100% LEL	75		wet, coarse, no silt	
25 26 8	na	BH-406-9A		10% LEL	100		SAND moist to wet, brown/grey, coarse, odours	303.00
27	na	BH-406-9B		5% LEL	100		wet, fine, some gravel	
28 29	na	BH-406-10A		375	100		GRAVEL wet, grey, faint odours	302.00
9	na	BH-406-10B		150	100		sandy GRAVEL wet, brown, some silt, faint odours	
30 31 32	na	BH-406-11		5% LEL	100		SAND wet, grey, medium to coarse, some gravel and silt, faint odours	301.00
33 10 34 35 36 11 37							End of borehole at 10.7 m bgs	300.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-501(MW-501)

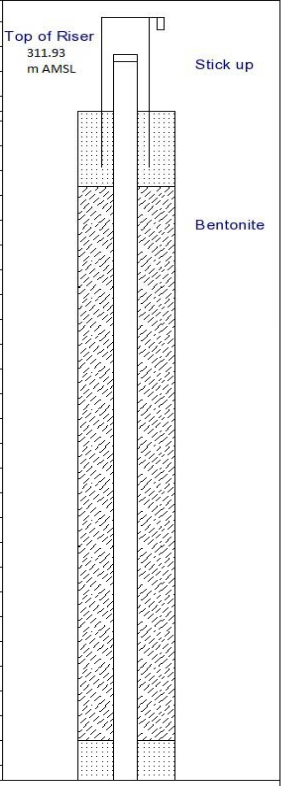
Page 1 of 2

Project No.:
Client:
Location:
Date Completed: July 15, 2009
Site Datum:

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter:

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75
Well Casing: Stick Up
Well Screen: U of W Multi-level

DEPTH (ft / m)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION m AMSL
0							Ground Surface	311.19
0							Not sampled	
								310.00
								309.00
								308.00
								307.00
15	na	BH-501-1		na	0		No recovery	
								306.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-501(MW-501)

Page 2 of 2

Project No.:
Client:
Location:
Date Completed: July 15, 2009
Site Datum:

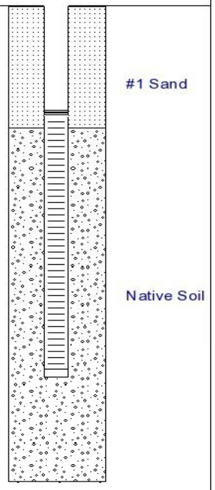
ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter:

Drilling Company: Geo-Environmental
Drilling Equipment: CME-75
Well Casing: Stick Up
Well Screen: U of W Multi-level

BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION
na	BH-501-2A		75% LEL	100		SAND and GRAVEL wet, grey, medium to coarse, cobbles, odours, grey staining and sheen on sample
na	BH-501-2B		>100% LEL	100		brown/grey, no staining
na	BH-501-3A		>100% LEL	100		gravelly SAND wet, brown, medium to coarse, cobbles, odours, grey staining from 6.5 m to 6.7 m bgs
na	BH-501-3B		>100% LEL	100		SAND moist to wet, brown, fine to medium, odours
na	BH-501-4A		>100% LEL	100		
na	BH-501-4B		40% LEL	100		very fine, staining at 7.3 m bgs
na	BH-501-4C		>100% LEL	100		
na	BH-501-4D		>100% LEL	100		gravel from 7.5 m to 7.55 m bgs
na	BH-501-5A		>100% LEL	100		gravelly SAND wet, grey, medium, cobbles, strong odours
na	BH-501-5B		5% LEL	100		SAND wet, brown, fine to very fine, faint odours
						End of borehole at 9.1 m bgs

DEPTH
18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
6 7 8 9 10 11

ELEVATION
305.00 304.00 303.00 302.00 301.00 300.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-601(MW-601)

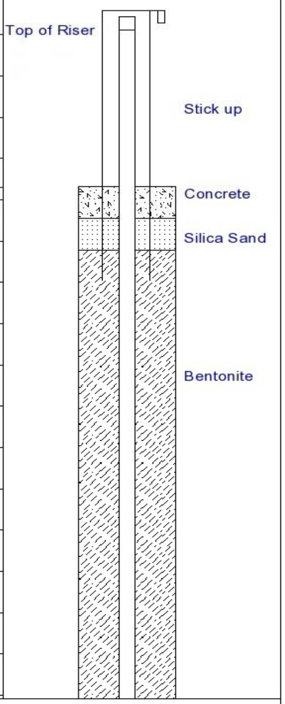
Page 1 of 3

Project No.:
Client:
Location:
Date Completed:
Site Datum.

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter: 3.2 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME- M75
Well Casing: Stick Up
Well Screen: 3.2 cm PVC size 10 slot

DEPTH ft	DEPTH m	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION m AMSL
-4									
-3									
-2									
-1									
									311.00
0	0							Ground Surface	310.97
								Not sampled	
1									
2									
3									310.00
	1								
4									
5									
6									309.00
	2								
7									
8									



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

AQUA TERRE

Borehole/Monitoring Well ID: BH-601(MW-601)

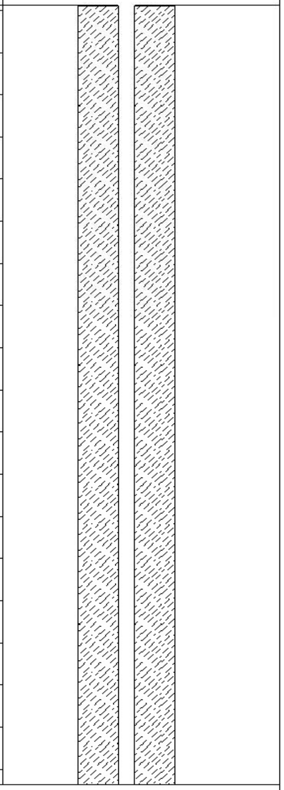
Page 2 of 3

Project No.:
Client:
Location:
Date Completed: October 27, 2009
Site Datum:

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter: 3.2 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME- M75
Well Casing: Stick Up
Well Screen: 3.2 cm PVC size 10 slot

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m)
9 3								308.00
10 11 12	na	BH-601-1		25% LEL	68		silty, gravelly SAND moist, grey, trace clay, fine to coarse gravel, fine sand, large cobbles, odours	
13 4 14	na	BH-601-2		70% LEL	54		dry to moist, light brown	307.00
15	na	BH-601-3A		85% LEL	79		SAND moist, brown, trace gravel, very fine to fine, odours	
16 5 17	na	BH-601-3B		40% LEL	79		gravelly SAND moist, grey, fine to coarse, odours	306.00
18 19 6 20	na	BH-601-4		80% LEL	73		moist to wet, brown/grey, trace silt black staining at 6.1 m bgs	305.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

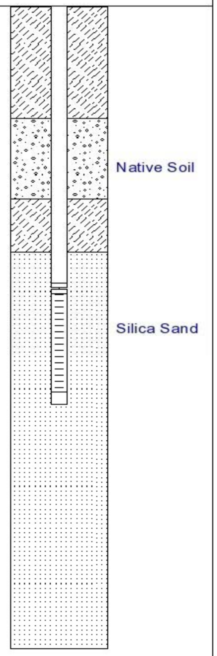
All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-601(MW-601)

Project No.:	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client:	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME- M75
Location:	**Borehole Diameter:** 21.0 cm	**Well Casing:** Stick Up
Date Completed: October 27, 2009	**Monitoring Well Diameter:** 3.2 cm	**Well Screen:** 3.2 cm PVC size 10 slot
Site Datum:		

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION m AMSL
21	na	BH-601-5A		>100% LEL	79		SAND wet, grey, fine, odours 2 cm brown SILT seam at 6.6 m bgs	
	na	BH-601-5B		50% LEL	79			
22	na	BH-601-5C		>100% LEL	79		fine to medium	
23 7	na	BH-601-6A		>100% LEL	74		free product at 7.0 m bgs	304.00
24 25	na	BH-601-6B		>100% LEL	74		brown/grey, fine, odours, no free product	
26 8	na	BH-601-7A		70% LEL	66			303.00
27	na	BH-601-7B		25% LEL	66		silty, gravelly SAND wet, light grey, fine to coarse sand, cobbles	
28 29 9	na	BH-601-8		225	98		sandy GRAVEL and SILT wet, grey, cobbles, odours	302.00
30 31 32							End of borehole at 9.1 m bgs	



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

Monitoring well equipped with dedicated inertial foot valve and polyethylene tubing for sampling.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-602 (MW-602)

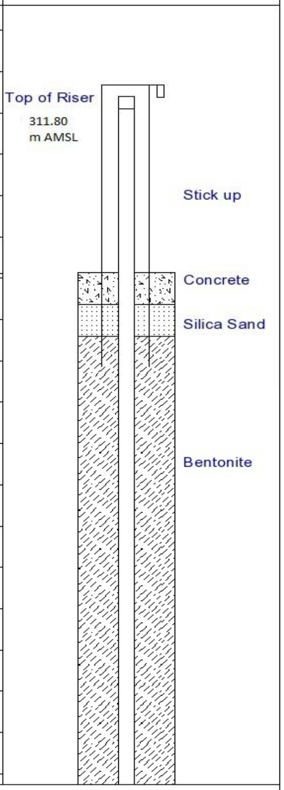
Page 1 of 3

Project No.:
Client:
Location:
Date Completed: October 28, 2009
Site Datum:

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter: 3.2 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME- M75
Well Casing: Stick Up
Well Screen: 3.2 cm PVC size 10 slot

DEPTH (ft / m)	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION (m AMSL)
0 / 0							Ground Surface	310.93
							Not sampled	
								310.00
								309.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-602 (MW-602)

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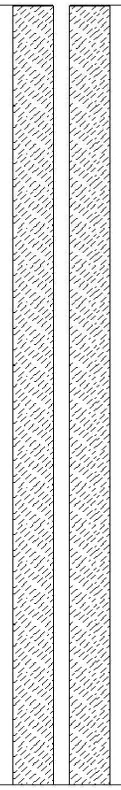
Project No.:
Client:
Location:
Date Completed: October 28, 2009
Site Datum:

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter: 3.2 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME- M75
Well Casing: Stick Up
Well Screen: 3.2 cm PVC size 10 slot

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION m AMSL
9 3								305.00
10 11 12	na	BH-602-1		15% LEL	61		silty, gravelly SAND moist to wet, grey, some clay, cobbles, odours	
13 4	na	BH-602-2A		75% LEL	59		SAND moist, brown/grey, fine, odours 1 cm SILT seam at 4.1 m bgs	304.00
	na	BH-602-2B		50% LEL	59			
14	na	BH-602-2C		30% LEL	59		gravelly SAND moist, grey, odours	
15	na	BH-602-3A		50% LEL	86			
16	na	BH-602-3B		375	86		SAND moist, brown, some silt, very fine, odours, staining at 4.9 m bgs	303.00
5	na	BH-602-3C		>100% LEL	86			
17	na	BH-602-3D		75% LEL	86		no silt, fine gravelly SAND dry to moist, brown/grey, odours, staining at 5.1 m bgs	
18	na	BH-602-4A		>100% LEL	76		SAND moist, brown, some gravel, fine to very fine, odours	
	na	BH-602-4B		>100% LEL	76			
19 6 20	na	BH-602-4C		>100% LEL	76		moist to wet, grey, no gravel, odours, black staining	302.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-602 (MW-602)

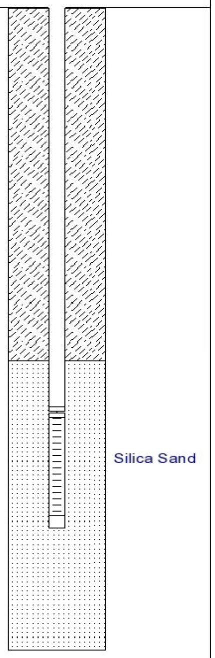
Page 3 of 3

Project No.:
Client:
Location:
Date Completed: October 28, 2009
Site Datum:

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter: 3.2 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME- M75
Well Casing: Stick Up
Well Screen: 3.2 cm PVC size 10 slot

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION m AMSL
	na	BH-602-5A		>100% LEL	81		moist, brown/grey, some gravel, fine to coarse sand 1cm silt seam at 6.0 m bgs	
21 22	na	BH-602-5B		>100% LEL	81		black staining from 6.0 m to 6.1 m bgs wet, grey, odours brown/grey, fine to very fine, 2 cm silt seam at 6.7 m bgs	
	na	BH-602-5C		>100% LEL	81		grey, trace gravel, medium to coarse	301.00
23 24	7 na	BH-602-6A		60% LEL	62		brown, fine, odours, 3 cm gravel seam at 7.0 m bgs sheen on sample from 7.1 to 7.3 m bgs	
25	na	BH-602-6B		5% LEL	62		silty, sandy GRAVEL wet, brown/grey	
	na	BH-602-7A		175	83		cobbles	300.00
26 27	8 na	BH-602-7B		475	83		SAND wet, brown/grey, some gravel, fine to medium	
28	na	BH-602-8A		375	52		no gravel	
29 30	na 9	BH-602-8B		400	52		silty, sandy GRAVEL moist, brown/grey	299.00
31 32							End of borehole at 9.1 m bgs	



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

Monitoring well equipped with dedicated inertial foot valve and polyethylene tubing for sampling.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-603 (MW-603)

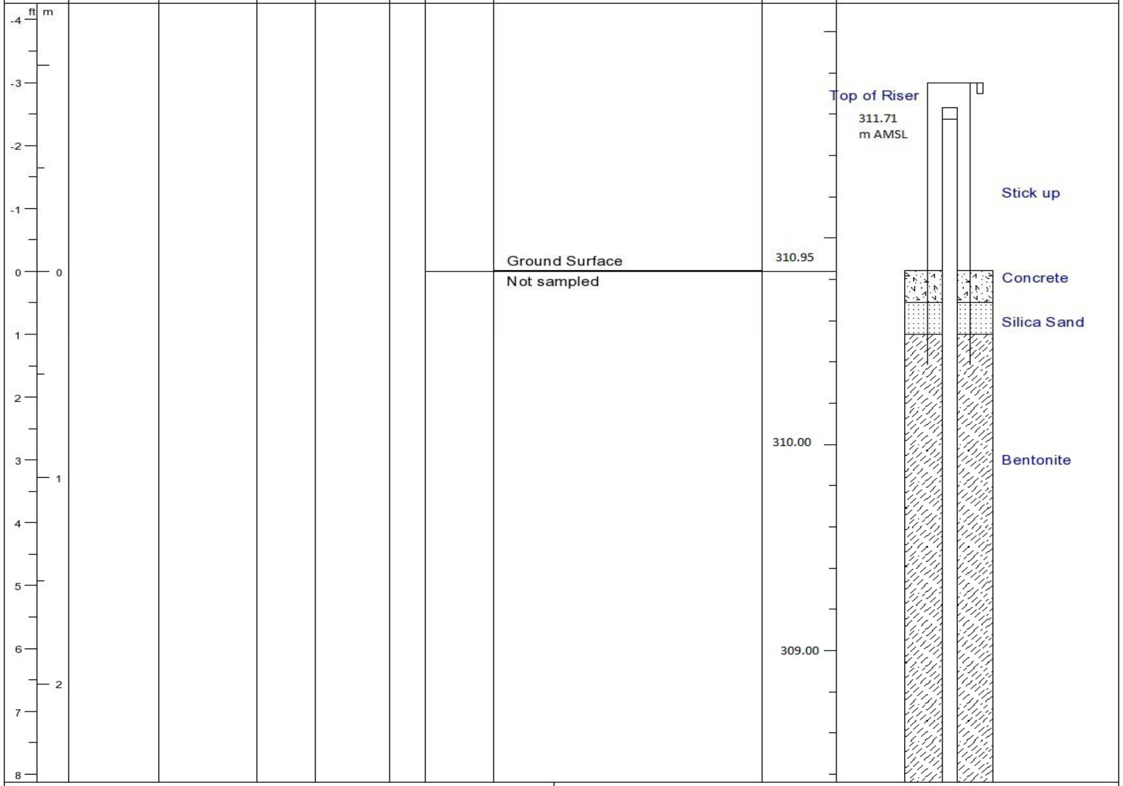
Page 1 of 3

Project No.:
Client:
Location:
Date Completed: October 28, 2009
Site Datum:

ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter: 3.2 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME- M75
Well Casing: Stick Up
Well Screen: 3.2 cm PVC size 10 slot

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	m AMSL ELEVATION	



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-603 (MW-603)

Page 2 of 3

Project No.:
Client:
Location:
Date Completed: October 28, 2009
Site Datum:

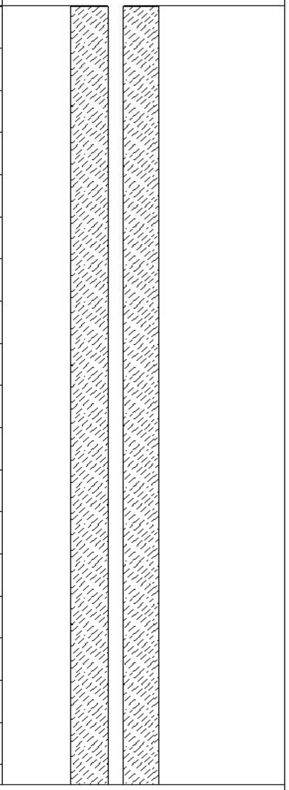
ATSI Supervisor: A. Reid
Drilling Method: Hollow Stem Auger
Borehole Diameter: 21.0 cm
Monitoring Well Diameter: 3.2 cm

Drilling Company: Geo-Environmental
Drilling Equipment: CME- M75
Well Casing: Stick Up
Well Screen: 3.2 cm PVC size 10 slot

DEPTH: 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 — 3, 4, 5, 6

BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION
na	BH-603-1		40% LEL	75		silty SAND and GRAVEL dry to moist, grey, cobbles, odours
na	BH-603-2		90% LEL	68		gravelly SAND moist, grey, medium to coarse, odours, dark grey staining from 3.8 m to 4.0 m bgs, 10 cm band of fine sand at 4.0 m bgs
na	BH-603-3A		35% LEL	74		
na	BH-603-3B		95% LEL	74		SAND moist, grey, some gravel, fine to medium, dark grey staining
na	BH-603-4A		>100% LEL	79		brown/grey, no gravel or staining
na	BH-603-4B		>100% LEL	79		brown, trace silt, very fine
na	BH-603-4C		>100% LEL	79		moist, brown/grey, some gravel, fine to coarse

ELEVATION: 308.00, 307.00, 306.00, 305.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

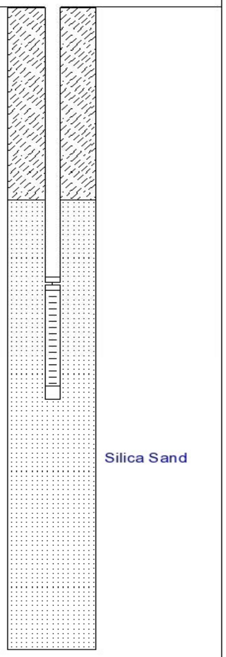
◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-603 (MW-603)

Page 3 of 3

Project No.:	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client:	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME- M75
Location:	**Borehole Diameter:** 21.0 cm	**Well Casing:** Stick Up
Date Completed: October 28, 2009	**Monitoring Well Diameter:** 3.2 cm	**Well Screen:** 3.2 cm PVC size 10 slot
Site Datum:		

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	m AMSL ELEVATION
21	na	BH-603-5A		>100% LEL	79		odours, 1 cm silt seam at 6.6 m bgs, black staining at 6.7m bgs	
22	na	BH-603-5B		500	79		gravelly SAND wet, brown/grey, medium to coarse, odours	304.00
23 — 7	na	BH-603-6A		5% LEL	79		SAND wet, brown, fine to medium, odours, rainbow sheen	
24	na	BH-603-6B		25% LEL	79		sandy GRAVEL wet, brown/grey, medium to coarse sand, cobbles, odours	
25 26 — 8	na	BH-603-7A		5% LEL	84		SAND wet, brown/grey, some gravel, medium	303.00
27	na	BH-603-7B		300	84		some silt, fine to very fine	
28 29 — 9	na	BH-603-8		200	63		gravelly, silty SAND wet, grey, fine to coarse	302.00
30 31 32							End of borehole at 9.1 m bgs	



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

Monitoring well equipped with dedicated inertial foot valve and polyethylene tubing for sampling.

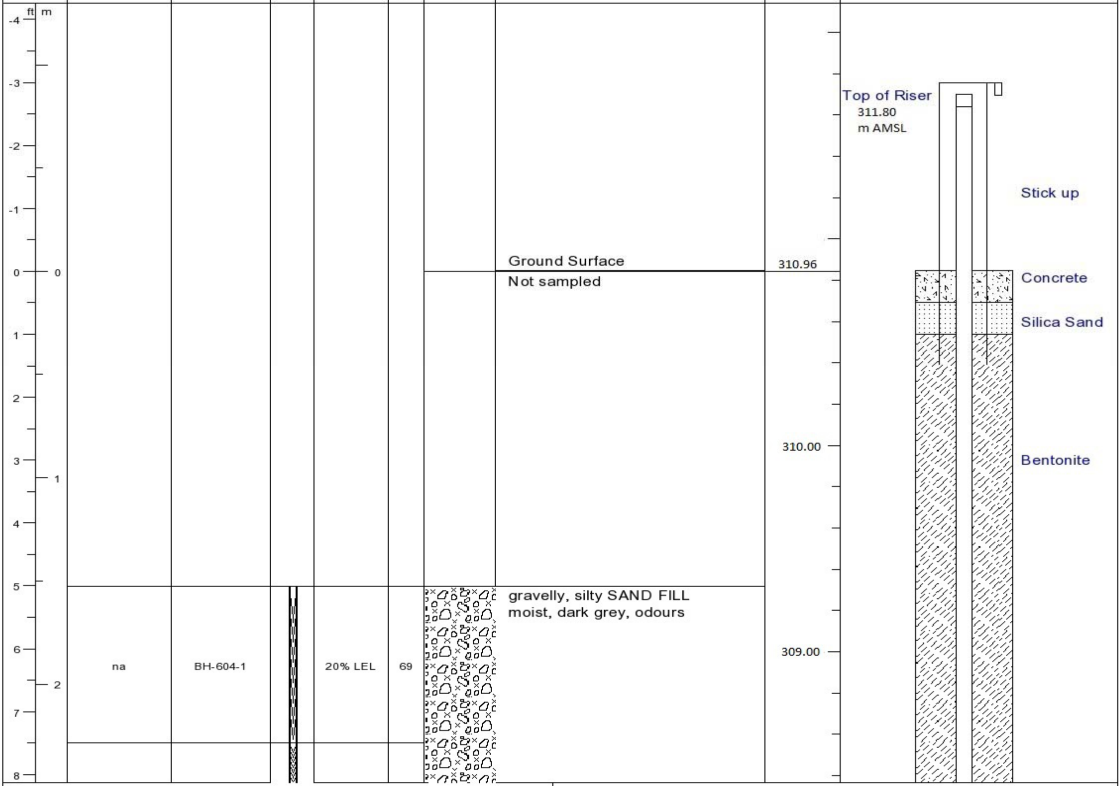
◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-604 (MW-604)

Page 1 of 3

Project No.:	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client.	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME- M75
Location:	**Borehole Diameter:** 21.0 cm	**Well Casing:** Stick Up
Date Completed: October 28, 2009	**Monitoring Well Diameter:** 3.2 cm	**Well Screen:** 3.2 cm PVC size 10 slot
Site Datum:		

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION m AMSL
0							Ground Surface Not sampled	310.96
5 ft	na	BH-604-1		20% LEL	69		gravelly, silty SAND FILL moist, dark grey, odours	



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

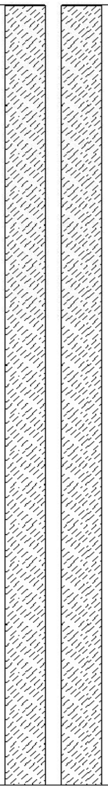
All elevations and locations are approximate.

◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-604 (MW-604)

Project No.:	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client:	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME- M75
Location:	**Borehole Diameter:** 21.0 cm	**Well Casing:** Stick Up
Date Completed: October 28, 2009	**Monitoring Well Diameter:** 3.2 cm	**Well Screen:** 3.2 cm PVC size 10 slot
Site Datum:		

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION
9 3	na	BH-604-2		25% LEL	63			308.00
10	na	BH-604-3A		25% LEL	72			
11 12	na	BH-604-3B		80% LEL	72		gravelly SAND moist, brown/grey, fine, odours	
13 4 14	na	BH-604-4		30% LEL	30		silty SAND moist, grey, cobbles, odours, black staining	307.00
15 16	na	BH-604-5A		30% LEL	92		SAND moist, brown/grey, some gravel, trace silt, medium to coarse, grey staining at 4.8 m bgs	306.00
5	na	BH-604-5B		20% LEL	92		silty SAND moist, brown/grey, trace gravel, very fine to medium	
17	na	BH-604-5C		70% LEL	92		SAND moist, brown/grey, some gravel, trace silt, medium to coarse, odours	
	na	BH-604-6A		100% LEL	91			
18	na	BH-604-6B		100% LEL	91		some silt, no gravel	
19 6 20	na	BH-604-6C		>100% LEL	91		moist to wet, brown, no silt, fine, grey staining in very fine sand at 5.8 m bgs	305.00



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

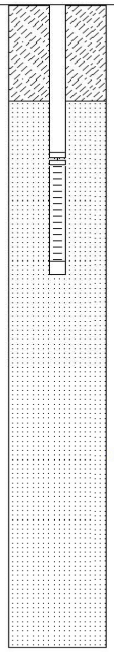
◆ = Sample submitted for laboratory analysis

Borehole/Monitoring Well ID: BH-604 (MW-604)

Page 3 of 3

Project No.:	**ATSI Supervisor:** A. Reid	**Drilling Company:** Geo-Environmental
Client:	**Drilling Method:** Hollow Stem Auger	**Drilling Equipment:** CME- M75
Location:	**Borehole Diameter:** 21.0 cm	**Well Casing:** Stick Up
Date Completed: October 28, 2009	**Monitoring Well Diameter:** 3.2 cm	**Well Screen:** 3.2 cm PVC size 10 slot
Site Datum:		

DEPTH	BLOW COUNT (1)	SAMPLE ID	LOCATION	OVM (2)	RECOVERY (%)	GRAPHIC LOG	DESCRIPTION	ELEVATION
21 22	na	BH-604-7		>100% LEL	100		wet, trace silt	304.00
23 — 7 24	na	BH-604-8A		15% LEL	84			
	na	BH-604-8B		225	84		gravelly, silty SAND wet, brown/grey, medium to coarse, cobbles	
25 26 — 8	na	BH-604-9A		75	84		silty, sandy GRAVEL wet, brown/grey	303.00
27	na	BH-604-9B		250	84		SAND wet, brown/grey, trace gravel, fine to coarse sand	
28 29	na	BH-604-10A		375	92		grey, fine	302.00
— 9	na	BH-604-10B		75	92		sandy, silty GRAVEL wet, grey	
30 31 32							End of borehole at 9.1 m bgs	



(1) Blow count per 0.15 m using conventional hammer and split spoons
(2) Organic Vapour Meter (OVM) reading (ppmv unless noted)

The data represented in this borehole log requires interpretation by Aqua Terre personnel. Third parties using this log do so at their own risk.

All elevations and locations are approximate.

Monitoring well equipped with dedicated inertial foot valve and polyethylene tubing for sampling.

◆ = Sample submitted for laboratory analysis

Table A.3 Historical groundwater elevations , estimation of horizontal hydraulic gradient and groundwater flow direction across the site

Date	Groundwater Elevations (m AMSL)				Horizontal Gradient	Groundwater Flow Direction Azimuth
	MW-4	MW-101	MW-103	MW-107		
2/25/2004	307.23	307.34	307.34	307.22	0.014	258
5/26/2004	308.56	308.71	308.71	308.62	0.011	253
6/18/2004	307.87	307.98	307.98	307.91	0.020	249
7/22/2004	306.99	307.07	307.07	307.03	0.013	240
8/27/2004	306.15	306.23	306.23	306.19	0.013	283
9/29/2004	305.47	305.54	305.54	305.49	0.008	270
11/9/2004	304.94	305.06	305.06	304.94	0.012	276
12/7/2004	304.95	305.05	305.05	304.95	0.009	280
12/21/2004	305.59	305.66	305.66	305.61	0.004	298
1/21/2005	307.22	307.27	307.27	307.21	0.006	263
4/19/2005	308.09	308.16	308.16	308.09	0.016	244
5/31/2005	307.56	307.62	307.62	307.56	0.015	244
6/29/2005	306.67	306.73	306.73	306.68	0.011	252
7/28/2005	305.95	306.01	306.01	305.97	0.007	263
8/25/2005	305.37	305.51	305.51	305.45	0.018	283
9/28/2005	305.08	305.27	305.27	305.15	0.012	291
10/27/2005	304.71	304.81	304.81	304.71	0.010	279
11/24/2005	304.64	304.77	304.77	304.65	0.012	280
12/22/2005	305.24	305.31	305.31	305.24	0.004	288
1/27/2006	306.91	306.95	306.95	306.91	0.004	273
2/23/2006	308.24	308.30	308.30	308.22	0.015	244
3/23/2006	309.42	309.56	309.56	309.45	0.016	240
4/27/2006	308.90	309.02	309.02	308.93	0.011	244
5/30/2006	307.65	307.71	307.71	307.67	0.010	242
6/29/2006	306.68	306.72	306.72	306.69	0.009	241
7/27/2006	306.11	306.17	306.17	306.13	0.005	264
8/24/2006	305.48	305.55	305.55	305.51	0.007	268
9/28/2006	304.95	305.05	305.05	304.95	0.010	277
10/30/2006	305.03	305.19	305.19	305.04	0.015	277
12/21/2006	306.70	306.73	306.73	306.68	0.006	280
1/24/2007	307.35	307.39	307.39	307.34	0.009	247
2/20/2007	306.91	306.95	306.95	306.90	0.009	246
3/20/2007	307.71	307.76	307.76	307.69	0.013	244
4/25/2007	309.12	309.26	309.26	309.14	0.022	249
6/7/2007	307.58	307.67	307.67	307.59	0.016	249.5
7/24/2007	306.12	306.17	306.17	306.14	0.007	255.5
9/6/2007	305.11	305.19	305.19	305.13	0.006	276
10/2/2007	304.70	304.80	304.80	304.71	0.009	282
11/7/2007	304.26	304.34	304.34	304.26	0.008	285
12/17/2007	304.10	304.19	304.19	304.09	0.007	280
1/22/2008	305.84	305.89	305.89	305.85	0.002	-
2/14/2008	306.65	306.70	306.70	306.64	0.003	295
3/19/2008	307.63	307.72	307.72	307.63	0.012	258
4/18/2008	309.78	309.98	309.98	309.87	0.012	259
5/28/2008	308.44	308.71	308.53	308.46	0.009	-
6/24/2008	308.39	308.61	308.45	308.40	0.010	240
7/30/2008	307.19	307.41	307.24	307.21	0.011	251
8/20/2008	306.56	306.70	306.61	306.57	0.006	250
9/26/2008	305.93	305.99	305.96	305.95	0.003	273
10/28/2008	305.49	305.57	305.59	306.53	0.009	299
11/20/2008	306.62	306.68	306.67	306.61	0.007	276
4/2/2009	-	309.87	309.86	309.75	0.012	262
5/27/2009	-	308.72	308.61	308.53	0.011	252
6/4/2009	-	308.62	308.50	308.41	0.013	240
6/25/2009	307.72	307.924	307.77	307.73	0.010	252
7/22/2009	306.81	307.01	306.85	306.82	0.007	247
7/28/2009	306.66	306.80	306.69	306.67	0.006	243
8/5/2009	306.43	306.14	306.46	306.45	0.006	247
8/10/2009	306.32	306.35	306.35	306.34	0.009	247
8/13/2009	306.26	306.29	306.29	306.27	0.007	260
8/25/2009	213.11	306.09	306.09	306.06	0.004	263
9/9/2009	305.70	305.77	305.77	311.01	0.008	273
1/21/2010	305.14	305.16	305.19	305.15	0.004	283
2/19/2010	305.26	305.29	305.32	305.28	0.004	293
3/22/2010	306.07	306.04	306.09	306.06	0.002	287
4/27/2010	305.85	305.88	305.89	305.85	0.003	275
5/19/2010	305.75	305.8	305.81	305.77	0.003	275
6/22/2010	305.69	305.74	305.77	305.72	0.006	280

Table A.4 Monthly monitoring field parameter measurements obtained from ATSI/SNC Lavalin using YSI 556

Monitoring Location	Date	Temperature (°C)	Dissolved Oxygen (mg/L)	Conductivity (µs/cm)	pH	Oxygen Reduction Potential (mV)
MW-1	25-Apr-07	nm	nm	nm	nm	nm
	8-Jun-07	11.3	4.7	nm	nm	nm
	24-Jul-07	nm	nm	nm	nm	nm
	6-Sep-07	nm	nm	nm	nm	nm
	2-Oct-07	nm	nm	nm	nm	nm
	22-Oct-08	nm	nm	nm	nm	nm
	20-Nov-08	nm	nm	nm	nm	nm
	17-Dec-08	nm	nm	nm	nm	nm
	28-Jan-09	nm	nm	nm	nm	nm
	5-Mar-09	nm	nm	nm	nm	nm
	2-Apr-09	nm	nm	nm	nm	nm
	27-Apr-09	5.7	0.8	1109	7	-75
	25-Jun-09	nm	nm	nm	nm	nm
	22-Jul-09	nm	nm	nm	nm	nm
	29-Aug-09	nm	nm	nm	nm	nm
MW-3	25-Apr-07	nm	8.3	nm	nm	nm
	8-Jun-07	9.7	7.6	nm	nm	nm
	24-Jul-07	10.7	7.7	nm	nm	nm
	6-Sep-07	nm	5.7	nm	nm	nm
	2-Oct-07	11.5	7.5	nm	nm	nm
	22-Oct-08	12	6.1	nm	nm	nm
	20-Nov-08	11.73	4.5	2210	6.7	77.3
	17-Dec-08	10.4	4.4	1737	6.8	79
	28-Jan-09	nm	nm	nm	nm	nm
	5-Mar-09	nm	nm	nm	nm	nm
	2-Apr-09	5.7	10.5	260	7.3	177.7
	27-Apr-09	7.1	8.8	323	6.9	137.6
	25-Jun-09	10.5	4.5	1280	7.3	49.5
	22-Jul-09	11.3	5	1621	7	233.5
	29-Aug-09	11.7	5.3	1700	7	73.2
MW-4	25-Apr-07	nm	6.9	nm	nm	nm
	7-Jun-07	9.1	1.4	nm	nm	nm
	24-Jul-07	9.9	2.7	nm	nm	nm
	6-Sep-07	nm	4.2	nm	nm	nm
	2-Oct-07	10.9	1.6	nm	nm	nm
	22-Oct-08	11.1	1.0	nm	nm	nm
	20-Nov-08	11.16	1.0	532	6.5	nm
	17-Dec-08	9.4	6.7	618	6.8	142.5
	28-Jan-09	6.9	2.8	454	6.6	132.6
	5-Mar-09	5.1	4.3	nm	nm	nm
	2-Apr-09	4.7	5.8	324	6.8	225.3
	27-Apr-09	6.2	6.8	320	7.1	121.3
	25-Jun-09	9.1	1.7	316	7.3	37
	22-Jul-09	10.4	0.98	404	7.2	156.8
	29-Aug-09	10.6	0.3	561	6.8	26
MW-5	25-Apr-07	nm	9.7	nm	nm	nm
	8-Jun-07	9.1	10.5	nm	nm	nm
	24-Jul-07	10.5	8.7	nm	nm	nm
	6-Sep-07	nm	5.3	nm	nm	nm
	2-Oct-07	11.3	7.4	nm	nm	nm
	22-Oct-08	11.8	6.2	nm	nm	nm
	20-Nov-08	11.8	6.5	1016	6.7	61.5
	17-Dec-08	10.2	7.1	862	6.9	56.5
	28-Jan-09	7.6	7.4	845	6.5	49.7
	5-Mar-09	5.9	7.4	nm	nm	nm
	2-Apr-09	5.6	12.3	714	7	174.4
	27-Apr-09	6.9	10.7	777	7.1	142.2
	25-Jun-09	9.7	7.6	962	7.1	64.3
	22-Jul-09	102	5.5	1187	6.9	225.5
	29-Aug-09	11.1	4.9	1224	6.8	82.6
MW-12	25-Apr-07	nm	8.4	nm	nm	nm
	8-Jun-07	nm	9.1	nm	nm	nm
	24-Jul-07	9.4	5.0	nm	nm	nm
	6-Sep-07	nm	9.3	nm	nm	nm
	2-Oct-07	11.2	7.1	nm	nm	nm
	22-Oct-08	10.4	5.4	nm	nm	nm
	20-Nov-08	11	5.5	541	6.7	66.7
	17-Dec-08	9	6.3	505	6.9	26.7

Table A.4 Monthly monitoring field parameter measurements obtained from ATSI/SNC Lavalin using YSI 556

Monitoring Location	Date	Temperature (^{o}C)	Dissolved Oxygen (mg/L)	Conductivity (µs/cm)	pH	Oxygen Reduction Potential (mV)
	28-Jan-09	7.4	6.4	456	6.6	125.9
	5-Mar-09	5.5	7.0	nm	nm	nm
	2-Apr-09	4.4	10.3	251	7.3	228.1
	27-Apr-09	5.6	9.6	344	7.1	141.9
	25-Jun-09	8.5	7.4	546	7.2	62.2
	22-Jul-09	8.8	6.4	572	6.9	217.1
	29-Aug-09	9.1	5.2	574	6.9	45.3
MW-101	25-Apr-07	nm	7.3	nm	nm	nm
	7-Jun-07	9.3	3.8	nm	nm	nm
	24-Jul-07	10.2	1.7	nm	nm	nm
	6-Sep-07	nm	2.6	nm	nm	nm
	2-Oct-07	11.2	0.7	nm	nm	nm
	22-Oct-08	11.8	1.1	nm	nm	nm
	20-Nov-08	11.39	1.0	980	6.55	62.8
	17-Dec-08	10.3	5.4	821	6.8	141.2
	28-Jan-09	7.1	5.5	962	6.5	154.6
	5-Mar-09	5.5	5.2	nm	nm	nm
	2-Apr-09	4.3	12.9	181	7.2	213.8
	27-Apr-09	6.3	9.9	254	7.2	227.2
	25-Jun-09	9.5	3.0	1965	6.9	81.3
	22-Jul-09	10.4	1.4	1781	6.2	313.6
	29-Aug-09	11	0.3	1765	6.8	90.4
MW-103	25-Apr-07	nm	0.7	nm	nm	nm
	7-Jun-07	9.7	1.4	nm	nm	nm
	24-Jul-07	9.8	2.0	nm	nm	nm
	6-Sep-07	nm	3.1	nm	nm	nm
	2-Oct-07	10.9	0.4	nm	nm	nm
	22-Oct-08	11.2	0.9	nm	nm	nm
	20-Nov-08	10.4	0.4	277	6.54	-54.8
	17-Dec-08	9.6	0.5	273	6.86	-64.2
	28-Jan-09	7.6	0.2	326	6.6	46.3
	5-Mar-09	5.6	5.3	nm	nm	nm
	2-Apr-09	4.5	6.0	156	7.1	169
	27-Apr-09	9	5.6	166	128.5	7.2
	25-Jun-09	8.9	0.6	356	7	28
	22-Jul-09	9.2	1.0	380	6.4	179.4
	29-Aug-09	10	0.2	815	6.9	-93.9
MW-106	25-Apr-07	nm	8.5	nm	nm	nm
	7-Jun-07	9.4	5.9	nm	nm	nm
	24-Jul-07	9.9	3.7	nm	nm	nm
	6-Sep-07	nm	3.1	nm	nm	nm
	2-Oct-07	10.9	1.5	nm	nm	nm
	22-Oct-08	11.3	1.7	nm	nm	nm
	20-Nov-08	11.5	5.4	1026	6.5	116
	17-Dec-08	9.2	6.7	618	6.8	142.5
	28-Jan-09	7	6.6	594	6.6	144.9
	5-Mar-09	4.6	9.1	nm	nm	nm
	2-Apr-09	4.3	8.6	282	6.62	243.9
	27-Apr-09	6.2	8.0	435	6.9	163.5
	25-Jun-09	9	3.7	1163	7.1	43.7
	22-Jul-09	10.1	2.7	1512	6.6	248.8
	29-Aug-09	10.4	0.8	1214	6.8	60.6
MW-107	25-Apr-07	nm	7.7	nm	nm	nm
	8-Jun-07	9.1	1.9	nm	nm	nm
	24-Jul-07	9.7	4.4	nm	nm	nm
	6-Sep-07	nm	3.1	nm	nm	nm
	2-Oct-07	10.8	0.4	nm	nm	nm
	22-Oct-08	11	1.1	nm	nm	nm
	20-Nov-08	11.2	3.3	484	6.5	43.2
	17-Dec-08	9.3	5.0	526	6.8	151.7
	28-Jan-09	6.9	5.7	447	6.5	133
	5-Mar-09	4.6	8.3	nm	nm	nm
	2-Apr-09	4.4	11.8	243	7	216.4
	27-Apr-09	6.4	9.9	328	7.1	142
	25-Jun-09	8.3	2.2	419	7.1	-1
	22-Jul-09	9.8	0.9	475	7	186.9
	29-Aug-09	10.2	0.9	437	6.9	33.7
MW-109	25-Apr-07	nm	nm	nm	nm	nm

Table A.4 Monthly monitoring field parameter measurements obtained from ATSI/SNC Lavalin using YSI 556

Monitoring Location	Date	Temperature (^oC)	Dissolved Oxygen (mg/L)	Conductivity (μs/cm)	pH	Oxygen Reduction Potential (mV)
	7-Jun-07	9.5	8.0	nm	nm	nm
	24-Jul-07	9.9	7.1	nm	nm	nm
	6-Sep-07	nm	6.1	nm	nm	nm
	2-Oct-07	11.7	7.0	nm	nm	nm
	22-Oct-08	12.1	6.2	nm	nm	nm
	20-Nov-08	112	6.9	1464	6.8	65.4
	17-Dec-08	10.6	6.9	1498	6.8	96.1
	28-Jan-09	nm	nm	nm	nm	nm
	5-Mar-09	nm	nm	nm	nm	nm
	2-Apr-09	5.7	8.2	938	7.1	234.9
	27-Apr-09	7	8.6	1083	7.2	123.1
	25-Jun-09	9.9	7.6	1205	7.2	70.5
	22-Jul-09	10.7	7.1	1456	7.1	233.5
	29-Aug-09	11.8	6.2	1594	7	63.2

June and September 2007 measurements were taken with a YSI 556 Multi-parameter meter with flow

nm	not monitored
ORP	lack of equilibrium between different redox couples in water sample (Stumm & Morgan, 1996) Difficult to determine meaningful ORP data in regards to the Nernst Equation, Eh higher for oxic than reduced environments (Appelo & Postma, 2007) Eh determines the distribution of all redox equilibria, although cnanont be measured unambiguously in most natural waters (Appelo & Postma, 2007)

Table A.5 Results of the historical groundwater quality monitoring program for petroleum hydrocarbons.

Well ID	Sample Date	Sample Type	Benzene	Toluene	Ethylbenzene	m,p xylene	o-xylene	Xylenes	F1	F2	F1+F2	F3	F4	F3+F4
		RDL	0.2	0.2	0.2	na	na	0.4	100	100	100	100	100	100
		MOE Standards	5	24	2.4	ns	ns	300	ns	ns	<1000	ns	ns	<1000
		MOE Criteria	5	24	2.4	nc	nc	300	nc	nc	nc	nc	nc	nc
MW-1	28-Oct-09	Sample	**64**	**2300**	**2300**	3100	8600	**12000**	32000	15000	**31000**	1700	<	**1700**
MW-4	28-Oct-09	Sample	**100**	23	**180**			**610**	1500	400	**1000**	<	<	<
	28-Oct-09	Field Duplicate	**96**	21	**170**			**570**	1600	370	**1100**	<	<	<
	27-Apr-10	Sample	0.8	<	1.7	1.2	3.8	5	<	<	<	<	<	<
	27-Apr-10	Field Duplicate	0.8	<	1.8	1.2	4.1	5.3	<	<	<	<	<	<
MW-5	16-Mar-99	Sample	4	4	2	1	1	2	-	-	-	-	-	-
	6-Apr-00	Sample	nd	nd	nd	nd	nd	nd	-	-	-	-	-	-
	6-Apr-00	Sample	nd	nd	nd	nd	nd	nd	-	-	-	-	-	-
	26-Feb-04	Sample	0.64	0.95	0.49	0.63	0.3	0.93	-	-	-	-	-	-
	29-Sep-04	Sample	nd	nd	nd	nd	nd	nd	-	-	-	-	-	-
	20-Apr-05	Sample	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
	28-Apr-06	Sample	<	0.6	0.3	<	<	<	<	<	<	<	<	<
	8-Jun-07	Sample	<	<	<	na	na	<	<	<	<	<	<	<
MW-12	16-Mar-99	Sample	<	<	<	<	<	nd	-	-	-	-	-	-
	6-Apr-00	Sample	5.93	0.66	nd	nd	nd	nd	-	-	-	-	-	-
	6-Apr-00	Field Duplicate	5.75	0.64	nd	nd	nd	nd	-	-	-	-	-	-
	26-Feb-04	Sample	nd	nd	nd	nd	nd	nd	-	-	-	-	-	-
	29-Sep-04	Sample	nd	nd	nd	nd	nd	nd	-	-	-	-	-	-
	19-Apr-05	Sample	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
	28-Apr-06	Sample	<	0.3	<	<	<	<	<	<	<	<	150	150
	8-Jun-07	Sample	<	<	<	na	na	<	<	<	<	<	<	<
	8-Jun-07	Lab Duplicate	-	-	-	na	na	-	-	<	<	-	<	<
	27-Apr-10	Sample	<	<	<	<	<	<	<	<	<	<	<	<
MW-101	28-Nov-01	Sample	**92.8**	6.06	**19.5**	7.7	1.21	8.91	-	-	-	-	-	-
	28-Nov-01	Lab Replicate	**96.6**	6.48	**20.7**	8.78	1.18	9.96	-	-	-	-	-	-
	26-Feb-04	Sample	**7.85**	1.47	**3.06**	2.74	1.69	4.43	-	-	-	-	-	-
	26-Feb-04	Lab Replicate	-	-	-	-	-	na	-	-	-	-	-	-
	30-Sep-04	Sample	1.51	0.29	0.28	1.09	0.51	1.6	-	-	-	-	-	-
	30-Sep-04	Replicate	-	-	-	-	-	na	-	-	-	-	-	-
	19-Apr-05	Sample	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
	27-Apr-06	Sample	<	<	<	<	<	<	<	<	<	<	<	<
	7-Jun-07	Sample	<	<	<	-	-	<	<	<	<	<	<	<
MW-103	28-Nov-01	Sample	**51.7**	**37.6**	**82.1**	208	44.6	252.6	-	-	-	-	-	-
	26-Feb-04	Sample	**19.6**	10.3	**66.3**	144	13.6	157.6	-	-	-	-	-	-
	30-Sep-04	Sample	**30**	10.7	**69.4**	109	15.9	124.9	-	-	-	-	-	-
	30-Sep-04	Sample	**4.14**	2.69	**58.1**	86.7	9.52	96.22	-	-	-	-	-	-
	19-Apr-05	Sample	**25.6**	9.27	**47.3**	96.8	16.3	113.1	723	3120	**3843**	900	nd	900
	27-Apr-06	Sample	**6**	3	**36**	73	6	79	763	3240	**4003**	960	nd	960
	7-Jun-07	Sample	2.3	2.9	**39**	-	-	77	1300	2600	**3900**	820	<	820
	27-Apr-10	Sample	0.5	0.9	11	1.7	14	16	210	7400	**7400**	4400	<	**4400**

Table A.5 Results of the historical groundwater quality monitoring program for petroleum hydrocarbons.

Well ID	Sample Date	Sample Type	Benzene	Toluene	Ethylbenzene	m,p xylene	o-xylene	Xylenes	F1	F2	F1+F2	F3	F4	F3+F4
		RDL	0.2	0.2	0.2	na	na	0.4	100	100	100	100	100	100
		MOE Standards	5	24	2.4	ns	ns	300	ns	ns	<1000	ns	ns	<1000
		MOE Criteria	5	24	2.4	nc	nc	300	nc	nc	nc	nc	nc	nc
MW-106	28-Nov-01	Sample	**66.8**	8.81	**4.56**	3.03	1.36	4.39	-	-	-	-	-	-
	26-Feb-04	Sample	**7.62**	1.29	0.49	0.79	2.69	3.48	-	-	-	-	-	-
	30-Sep-04	Sample	**13.8**	1.58	0.35	0.77	0.32	1.09	-	-	-	-	-	-
	19-Apr-05	Sample	1.81	0.62	1.56	3.41	1.59	5	nd	nd	nd	nd	nd	nd
	27-Oct-05	Sample	2.3	<	<	<	<	<	<	<	<	<	<	<
	27-Apr-06	Sample	12	0.7	3.9	8.1	2.9	11	<	<	<	<	<	<
	30-Oct-06	Sample	**10**	0.6	<	<0.2	<0.4	<	<	<	<	<	<	<
	7-Jun-07	Sample	**5.3**	<	**4.3**	-	-	9.7	<	<	<	<	<	<
	2-Oct-07	Sample	4.3	0.3	<	-	-	0.7	<	<	<	<	<	<
	28-Oct-09	Sample	1	1	1			<	<	<	<	<	<	<
	28-Oct-09	Lab Dup	1	1	1	1	1	<	<	<	<	<	<	<
	27-Apr-10	Sample	<	<	<	<	<	<	<	<	<	<	<	<
MW-107	29-Nov-01	Sample	**16.3**	8.59	**5.3**	7.54	3.25	10.79	-	-	-	-	-	-
	26-Feb-04	Sample	**8.75**	4.59	**12.6**	10.3	2.4	12.7	-	-	-	-	-	-
	29-Sep-04	Sample	**11.6**	2.49	**17.4**	12.2	4.54	16.74	-	-	-	-	-	-
	19-Apr-05	Sample	2.59	0.62	**5.09**	5.22	1.33	6.55	105	476	581	nd	nd	nd
	27-Oct-05	Sample	1.3	0.5	**6.8**	1.9	1.1	3.1	120	430	550	<	<	<
	27-Oct-05	Field Duplicate	1.4	0.5	**7**	2	1.1	3.1	<	450	450	<	<	<
	27-Apr-06	Sample	1.1	0.3	**7.2**	11	1	12	220	120	340	<	<	<
	30-Oct-06	Sample	2.2	1.3	**21**	3.8	24	28	330	770	**1100**	<	<	<
	8-Jun-07	Sample	1.6	0.8	**11**	-	-	22	390	740	**1130**	<	<	<
	2-Oct-07	Sample	1.5	0.8	**15**	-	-	8.5	200	330	530	<	<	<
	28-Oct-09	Sample	0.5	0.6	**18**	1.5	21	22	580	880	**1400**	<	<	<
	27-Apr-10	Sample	0.5	<0.2	**6.3**	0.4	5.2	5.6	<	290	290	<	<	<
MW-109	29-Nov-01	Sample	4.22	6.63	2.1	1.33	1.04	2.37	-	-	-	-	-	-
	29-Nov-01	Field Duplicate	3.88	5.97	1.8	1.16	0.89	2.05	-	-	-	-	-	-
	26-Feb-04	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	29-Sep-04	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	20-Apr-05	Sample	nd	nd	nd	nd	nd	nd	-	nd	nd	nd	nd	nd
	27-Apr-06	Sample	<	0.3	<	<	<	<	-	<	<	<	<	<
	7-Jun-07	Sample	<	<	<	-	-	<	-	<	<	<	<	<
	27-Apr-10	Sample	<	<	<	-	-	<	-	<	<	<	<	<
MW-201	26-Nov-02	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	10-Apr-03	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	9-Jul-03	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	25-Aug-06	Sample	<	<	<	<	<	<	-	<	<	<	<	<
	8-Jun-07	Sample	<	<	<	na	na	<	na	<	<	<	<	<
	28-Oct-09	Sample	<	<	<	na	na	<	na	<	<	<	<	<
	27-Apr-10	Sample	<	<	<	na	na	<	na	<	<	<	<	<

Table A.5 Results of the historical groundwater quality monitoring program for petroleum hydrocarbons.

Well ID	Sample Date	Sample Type	Benzene	Toluene	Ethylbenzene	m,p xylene	o-xylene	Xylenes	F1	F2	F1+F2	F3	F4	F3+F4
		RDL	0.2	0.2	0.2	na	na	0.4	100	100	100	100	100	100
		MOE Standards	5	24	2.4	ns	ns	300	ns	ns	<1000	ns	ns	<1000
		MOE Criteria	5	24	2.4	nc	nc	300	nc	nc	nc	nc	nc	nc
MW-202	25-Nov-02	Sample	**166**	**85.9**	**307**	1100	22.4	**1122.4**	3600	-	-	-	-	-
	9-Apr-03	Sample	**59.2**	19.4	**84.8**	316	6.08	**322.08**	1470	-	-	-	-	-
	9-Apr-03	Field Duplicate	**61.2**	19.7	**86.2**	322	5.87	**327.87**	1520	-	-	-	-	-
	9-Jul-03	Sample	**220**	**135**	**207**	677	42.5	**719.5**	3600	-	-	-	-	-
	9-Jul-03	Field Duplicate	**187**	**119**	**184**	589	37.3	**626.3**	2700	-	-	-	-	-
	25-Aug-06	Sample	**12**	3.8	**20**	54	0.6	54	-	<	<	<	<	<
	7-Jun-07	Sample	**29**	**30**	**160**	na	na	**550**	na	500	**1600**	<	<	<
	28-Oct-09	Sample	**5.3**	**4.8**	**80**	2.2	190	190	**1200**	**630**	**1600**	<	<	<
	27-Apr-10	Sample	0.2	1.2	22	0.9	37	38	230	110	280	<	<	<
MW-203	25-Nov-02	Sample	2.8	4	**39.3**	40.1	3.46	43.56	240	-	-	-	-	-
	9-Apr-03	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	9-Jul-03	Sample	nd	0.57	0.43	nd	nd	nd	nd	-	-	-	-	-
	25-Aug-06	Sample	<	<	0.9	<	<	<	-	<	<	<	<	<
	8-Jun-07	Sample	<	<	33	na	na	46	na	100	230	<	<	<
	28-Oct-09	Sample	<	<	<	na	na	<	na	<	<	<	<	<
	27-Apr-10	Sample	<	<	<	na	na	<	na	<	<	<	<	<
MW-204	25-Nov-02	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	9-Apr-03	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	8-Jul-03	Sample	nd	0.68	0.36	nd	nd	nd	nd	-	-	-	-	-
	25-Aug-06	Sample	<	<	<	<	<	<	-	<	<	<	<	<
	8-Jun-07	Sample	<	<	<	na	na	<	na	<	<	<	<	<
	28-Oct-09	Sample	<	<	<	na	na	<	na	<	<	<	<	<
	27-Apr-10	Sample	<	<	<	na	na	<	na	<	<	<	<	<
MW-205	26-Nov-02	Sample	1.11	1.56	0.71	nd	0.33	0.33	nd	-	-	-	-	-
	9-Apr-03	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	8-Jul-03	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	25-Aug-06	Sample	<	<	<	<	<	<	-	<	<	<	<	<
	25-Aug-06	Field Duplicate	<	<	<	<	<	<	-	<	<	<	<	<
	7-Jun-07	Sample	<	<	<	na	na	<	na	<	<	<	<	<
	7-Jun-07	Lab Duplicate	<	<	<	na	na	<	na	-	-	-	-	-
	28-Oct-09	Sample	<	<	<	<	<	<	-	<	<	<	<	<
	27-Apr-10	Sample	<	<	<	<	<	<	-	<	<	<	<	<

Table A.5 Results of the historical groundwater quality monitoring program for petroleum hydrocarbons.

Well ID	Sample Date	Sample Type	Benzene	Toluene	Ethylbenzene	m,p xylene	o-xylene	Xylenes	F1	F2	F1+F2	F3	F4	F3+F4
		RDL	0.2	0.2	0.2	na	na	0.4	100	100	100	100	100	100
		MOE Standards	5	24	2.4	ns	ns	300	ns	ns	<1000	ns	ns	<1000
		MOE Criteria	5	24	2.4	nc	nc	300	nc	nc	nc	nc	nc	nc
MW-206	26-Nov-02	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	26-Nov-02	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	10-Apr-03	Sample	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
	9-Jul-03	Sample	0.78	0.42	0.22	nd	nd	nd	nd	-	-	-	-	-
	25-Aug-06	Sample	<	<	<	<	<	<	-	<	<	<	<	<
	8-Jun-07	Sample	0.4	0.3	0.9	-	-	1	na	<	<	<	<	<
	8-Jun-07	Lab Duplicate	-	-	-	-	-	-	na	-	<	-	<	<
	28-Oct-09	Sample	<	<	<	0.6	<	0.6	<	<	<	<	<	<
	27-Apr-10	Sample	<	<	<	<	<	<	<	<	<	<	<	<

Note: Concentrations in ug/L (unless noted)

RDL	Reportable Detection Limit
na	not applicable
-	not analysed
nd / <	not detected above RDL provided
nc	no criterion
ns	no standard
-	not analyzed
Xylenes	sum of o-xylene and m,p-xylenes
TPH (Gas/Diesel)	sum of purgeable and extractable hydrocarbons
[1]	Table 2 full depth generic site condition standards in a potable groundwater condition for all types of property use (MOE,
[2]	Table A industrial/commercial criteria for fine/medium textured soils in a potable groundwater condition (MOEE, 1997).
1	Table A industrial/commercial criteria for fine/medium textured soils in a potable groundwater condition (MOEE, 1997).
<u>500</u>	exceeds groundwater criterion/standard

Table A.6 Monthly monitoring field parameter measurements obtained from ATSI/SNC Lavalin using YSI 556

Monitoring Location	Depth	Dissolved Oxygen (mg/L)	Temperature* (^{o}C)	Conductivity (µs/cm)	pH	Oxygen Reduction Potential (mV)
MW-301-7	313.50	0.15	12.36	1836	6.85	-45
MW-301-8	312.50	0.1	12.48	1862	6.82	-65
MW-301-9	311.50	0.17	11.44	1317	6.72	-67.4
MW-301-10	310.50	0.34	14.14	1836	6.74	-60.6
MW-301-11	309.50	0.43	15.46	1993	6.8	-58.4
MW-301-12	308.50	0.27	13.5	1424	6.7	-70.6
MW-302-6	314.23	0.22	13.33	1775	6.66	-80.5
MW-302-7	313.23	0.35	12.88	1747	6.64	-79.8
MW-302-8	312.23	0.47	14	1523	6.73	-92.3
MW-302-9	311.23	0.29	12.94	1380	6.78	-83.7
MW-302-10	310.23	0.7	15.79	1497	6.7	-87.6
MW-302-11	309.23	0.66	16.05	1503	6.72	-87.1
MW-302-12	308.23	0.45	14.81	1465	6.72	-86.2
MW-302-13	307.23	0.27	10.46	1248	6.7	-76.9

ORP	lack of equilibrium between different redox couples in water sample (Stumm & Morgan, 1996)
	Difficult to determine meaningful ORP data in regards to the Nernst Equation, Eh higher for oxic than reduced environments (Appelo & Postma, 2007)
	Eh determines the distribution of all redox equilibria, although cnanont be measured unambiguously in most natural waters (Appelo & Postma, 2007)
Measurements	Geochemical parameters were monitored by placing the probe in an air tight flow through cell.
	* temperature measurements are likely higher than groundwater conditions due to surface warming during the pumping of sample

Table A.7 Summary of bulk hydraulic conductivity estimates at injection well MW-501, situated in Unit 3 and Unit 4.

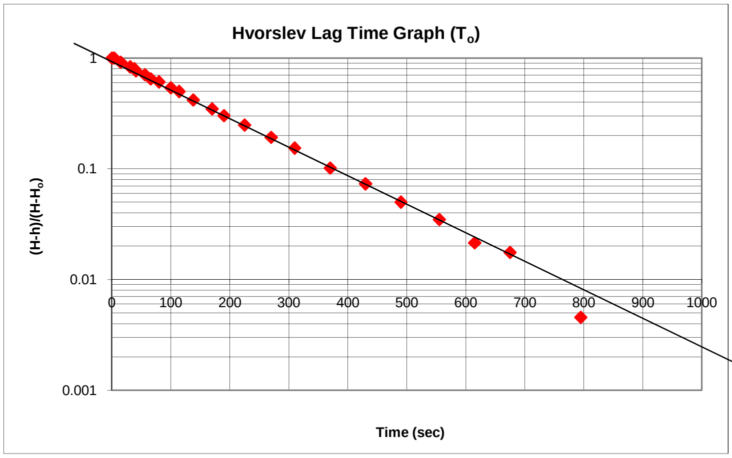
Test Date	Test No.	Water Level m AMSL	Length of Test Interval (m)	H_o (m br)	K (m/s)	Slug Test Method	Comments
28-Jul-10	1	306.59	3.20	8.42	2.3E-06	Rising Head Test	Analysed with Hvorslev
28-Jul-10	2	306.59	3.20	8.42	2.7E-06	Rising Head Test	Analysed with Hvorslev
8-Nov-10	1	305.17	1.97	6.48	4.1E-06	Falling Head Test	Analysed with Hvorslev
8-Nov-10	2	305.17	1.97	6.89	6.0E-06	Falling Head Test	Analysed with Hvorslev
8-Nov-10	3	305.17	1.97	6.63	3.2E-06	Falling Head Test	Analysed with Hvorslev
8-Nov-10	4	305.17	1.97	6.63	6.0E-06	Falling Head Test	Analysed with Hvorslev
8-Nov-10	5	305.17	1.97	6.15	4.6E-06	Falling Head Test	Analysed with Hvorslev
8-Nov-10	6	305.17	1.97	6.29	3.6E-06	Falling Head Test	Analysed with Hvorslev
8-Nov-10	7	305.17	1.97	6.31	2.3E-06	Falling Head Test	Analysed with Hvorslev

m AMSL Groundwater Elevaiton metres above mean sea level
m br metres below riser

Pre-Injection K (July 28, 2009)	2.5E-06	m/s
Pre-Injection σ	3.0E-07	m/s
Average Post-Injection K	4.3E-06	m/s
σ Post-Injection K	1.4E-06	m/s
Relative difference Pre- and Post-Injection	13	%

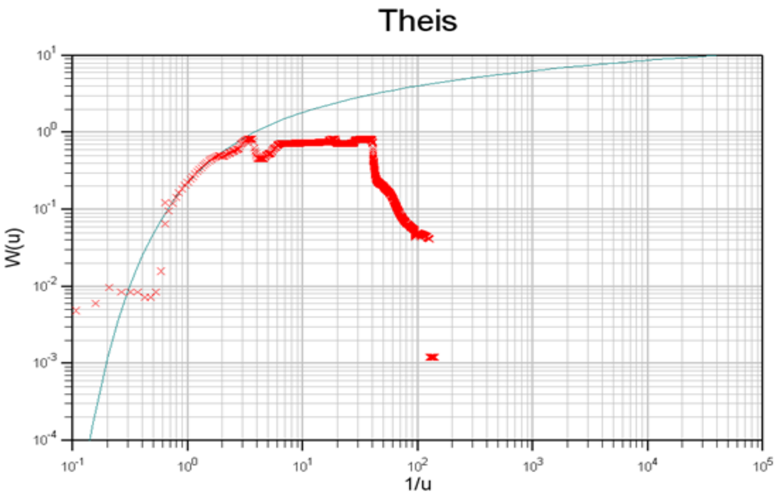
Example Hvorslev Calculation
(for Hydraulic Conductivity from Rising Head Tests)
Hvorslev Formula: $K = [\ r^2 \ln(L/R)\ ]/\ [\ 2LT_o\ ]$

Well Name = MW-501
Date: **28-Jul-10**
Initial WL (H) = 5.34 m (Static)
Radius of pipe (r) = 0.026 m
Radius of hole (R) = 0.102 m
Length of screen (L) = 3.200 m
$H\text{-}H_o$ = 3.078 m
Lag time (T_o) = 160 sec (t at $(H\text{-}h)/(H\text{-}H_o) = 0.37$ on graph)
H_o 8.420 m
Hydraulic Cond.(K) = **2.3E-06** m/s
2.3E-04 cm/s



Time (sec)	WL (m)	H-h (m)	(H-h)/(H-Ho)
0	8.42	3.078 m	1
4	8.42	3.08	1.00
15	8.165	2.82	0.92
31	7.9	2.56	0.83
38	7.8	2.46	0.80
41	7.7	2.36	0.77
56	7.515	2.17	0.71
66	7.34	2.00	0.65
80	7.214	1.87	0.61
100	7	1.66	0.54
114	6.877	1.54	0.50
138	6.629	1.29	0.42
170	6.408	1.07	0.35
190	6.272	0.93	0.30
225	6.106	0.76	0.25
270	5.934	0.59	0.19
310	5.815	0.47	0.15
370	5.655	0.31	0.10
430	5.567	0.23	0.07
490	5.496	0.15	0.05
555	5.449	0.11	0.03
615	5.408	0.07	0.02
675	5.396	0.05	0.02
795	5.356	0.01	0.00

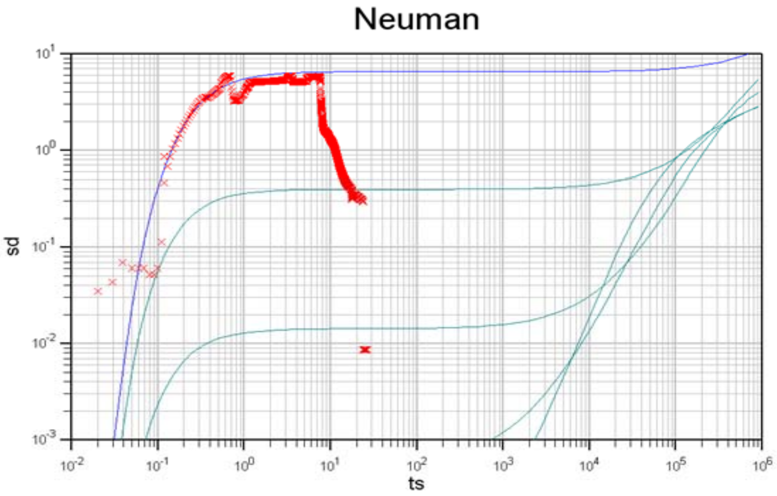
Analysis of the reverse aquifer pumping test results at injection well MW-501 screened within sand and gravel Unit 3 and sand Unit 4



Best Fit Aquifer Paremeters

Transmissivity = 2x10^{-5} m^2/s

Storativity = 6x10$^{-7,}$ β = 0.001 **not valid

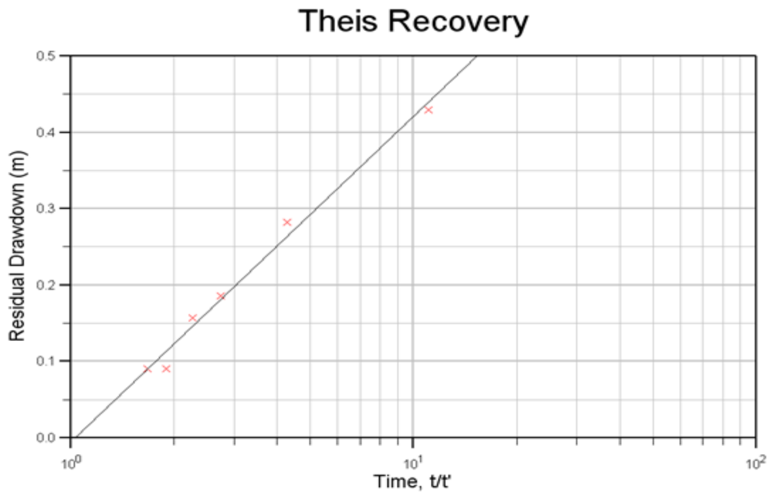


Best Fit Aquifer Paremeters

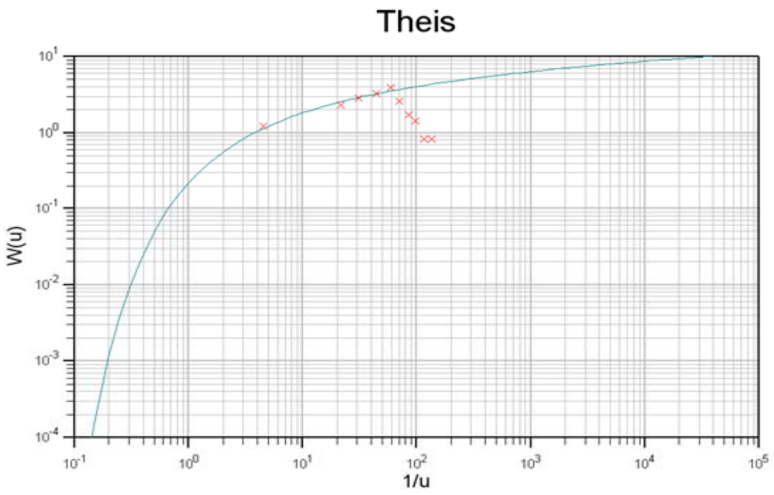
Transmissivity = 1x10^{-4} m^2/s

Storativity = 6x10$^{-6,}$ β = 0.001 **not valid

Analysis of the reverse aquifer pumping test results at observation well MW-401-4 screened within sandy Unit 4



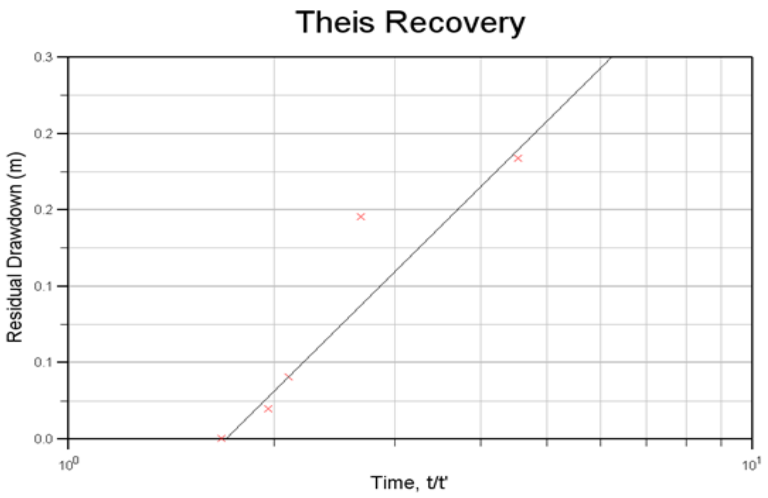
Best Fit Aquifer Paremeters
Transmissivity = $2x10^{-4}$ m^2/s
Storativity = NA



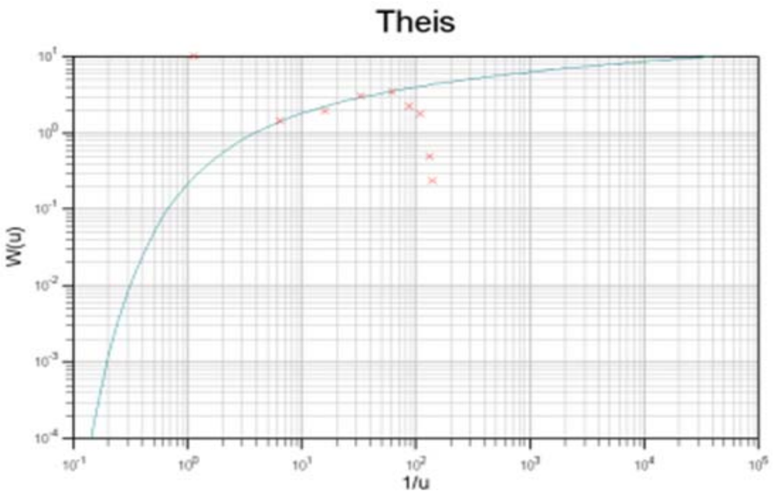
Best Fit Aquifer Paremeters
Transmissivity = $4x10^{-4}$ m^2/s
Storativity = 0.02

MW ID	Time (min)	WL Elevation (m AMSL)	Rise in WL (m)
MW-401-4	0	305.06	0
	5	305.20	0.13
	24	305.32	0.25
	34.5	305.37	0.31
	49	305.42	0.36
	66	305.49	0.43
	78.5	305.34	0.28
	95	305.25	0.19
	108	305.22	0.16
	128	305.15	0.09
	150	305.15	0.09
		WL at 95% Recovery (m)	0.02
		Actual % Recovery	79

Analysis of the reverse aquifer pumping test results at observation well MW-402-4 screened within sand and gravel Unit 3



Best Fit Aquifer Paremeters
Transmissivity = 2x10^{-4} m^2/s
Storativity = NA



Best Fit Aquifer Paremeters
Transmissivity = 5x10^{-4} m^2/s
Storativity = 0.02

MW ID	Time (min)	WL Elevation (m AMSL)	Rise in WL (m)
MW-402-4	0	305.07	0.00
	6	305.21	0.14
	14	305.26	0.19
	29	305.37	0.30
	42	305.43	0.22
	55	305.55	0.34
	77	305.43	0.22
	96	305.39	0.17
	115	305.26	0.05
	123	305.24	0.02
	150	305.21	0.00
		WL at 95% Recovery (m)	0.02
		Actual % Recovery	100

Table A.8 Comparison of the bromide (Br-) tracer breakthrough observed during a series of single-well point dilution tests conducted at various depths in multilevel well MW-301 and PULSEPE best-fit solution for 1D advection-dispersion equation.

MW-301-7			MW-301-9			MW-301-12		
Time (Hrs)	Observed Br$^-$ C/C$_o$	PULSPE Best Fit Br$^-$ C/C$_o$	Time (Hrs)	Observed Br$^-$ C/C$_o$	PULSPE Best Fit Br$^-$ C/C$_o$	Time (Hrs)	Observed Br$^-$ C/C$_o$	PULSPE Best Fit Br$^-$ C/C$_o$
0.0	1	0	0.0	0.97	0	0.0	0	0
0.1	1	0.99	0.2	0.97	0.89	0.0	0.94	0.01
0.3	0.86	1.01	0.3	0.93	1.23	0.2	0.88	0.87
0.3	0.74	0.84	0.5	0.92	0.79	0.2	0.86	0.93
0.4	0.68	0.58	0.7	0.79	0.53	0.3	0.78	0.85
0.5	0.59	0.43	0.8	0.52	0.38	0.5	0.58	0.43
0.6	0.54	0.34	1.0	0.37	0.28	0.7	0.42	0.29
0.8	0.37	0.23	1.2	0.24	0.21	0.8	0.29	0.22
1.2	0.21	0.12	1.3	0.16	0.16	1.0	0.18	0.18
1.6	0.1	0.07	1.5	0.07	0.13	1.2	0.18	0.15
2.0	0.04	0.04	1.7	0.08	0.10	1.3	0.13	0.13
2.4	0	0.03	1.8	0.04	0.08	1.5	0.09	0.11
2.8	0	0.02	2.0	0.01	0.06	1.7	0.08	0.10
3.2	0	0.01	2.2	0.02	0.05	1.8	0.05	0.09
3.6	0	8.0E-03	2.3	0	0.04	2.0	0.06	0.08
4.0	0	5.3E-03	2.5	0	0.03	2.2	0.05	0.07
4.4	0	3.6E-03	2.7	0	0.03	2.3	0.04	0.07
4.8	0	2.4E-03	2.8	0	0.02	2.5	0.04	0.06
			3.0	0	0.02	2.7	0.03	0.06
			3.2	0	0.01	2.8	0.03	0.05
			3.3	0	0.01	3.0	0.02	0.05
			3.5	0	9.5E-03			
			3.7	0	7.8E-03			
			3.8	0	6.4E-03			
			4.0	0	5.2E-03			
			4.2	0	4.3E-03			
			4.3	0	3.5E-03			
			4.5	0	2.9E-03			

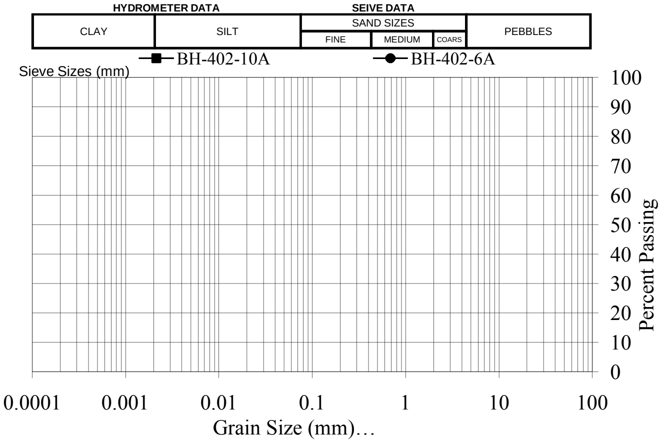
Grain Size Analysis Test Method

A total of 114 sediment samples were collected in the field during the well installations taking place during November 2007 (10 samples) and July 2009 (104 samples). Samples were retrieved for grain size analysis from intact core recovered from the hollow-auger split spoon sampler following the collection of samples for soil extraction analysis of BTEX, TMB and naphthalene contaminants (BTEXTMB). One sample was collected for grain size analysis per soil type identified within each spoon sample recovered, with additional samples being collected corresponding to signs of contaminant impacted areas. The soil constituents of each core were identified using the Unified Soil Classification System (ASTM, 1985), photographed and measured to determine the appropriate vertical distribution within the borehole log prepared by SNC Lavalin Inc. Soil subsamples were labeled and placed in a designated sealed plastic bag and measured for volatiles using the organic vapour meter after time had been allotted for volatile organic compounds to partition from the soil into the vapour phase. In the event where a portion of the soil core retrieved was representative of one single soil type, multiple subsamples were collected throughout the entire core and an average representative sample was prepared.

Grain size analysis of each sample was conducted following the ASTM protocol D 422-63 (ASTM, 2007). The effective grain diameters d_{10} and d_{60} (where 10% and 60% are finer than) were determined and uniformity coefficient, U calculated using equation (A.1):

$$U = \frac{d_{60}}{d_{10}} \qquad \text{(A.1)}$$

The test protocol involved passing a known mass of homogenized (using the riffle splitter), oven-dried soil through a set of sieves and measuring the amount of mass retained in each sieve. Hydrometer analysis was performed on 52 samples where the fraction retained on sieve No. 230 (0.0625 mm) exceeded 10%, d_{10}. Grain size distribution curves were prepared for each soil sample using the sieve analysis and hydrometer data when appropriate. The results of the grain size analysis are presented in Table A.9 of Appendix A. The aquifer materials range from poorly sorted sand and gravel mixtures, silty sand, to well sorted sand. Examples of the grain size distribution of a poorly sorted sand and gravel with trace silt sediment type and a well sorted sand with trace silt collected from BH-402 at a depth of 5.47 m bgs (305.62 m AMSL) and 8.53 m bgs (302.56 m AMSL) respectively, is shown the figure below.



Example grain size distribution of sorted sediment (BH-402-6A) obtained from the heterogeneous aquifer.

The Hazen approach (1892) was applicable in estimating hydraulic conductivity for the 24 samples that were well sorted with a uniformity coefficient, U, less than 5 and the effective grain size was between 0.1 and 3 mm. Hydraulic conductivity estimates were calculated using the physical properties of groundwater at 10°C as shown in equations (A.2) and (A.3).

$$v = \frac{\mu}{\rho} \qquad \text{(A.2)}$$

$$K = \frac{g}{v} * 6x10^{-4}[1 + 10(n - 0.26)]d_{10}^{2} \qquad \text{(A.3)}$$

Where:

K - hydraulic conductivity (m/s);

g - acceleration due to gravity (m/s^2);

v - kinematic velocity (m^2/s);

μ – dynamic velocity (1.307×10^{-6} s/m^2 at 10°C);

ρ - density of water (999.7026 kg/m^3 at 10°C).

Hydraulic conductivity was estimated using the Schlichter Method (1905) for medium grained sands with d_{10} between 0.01 and 5 mm represented by equation (A.4):

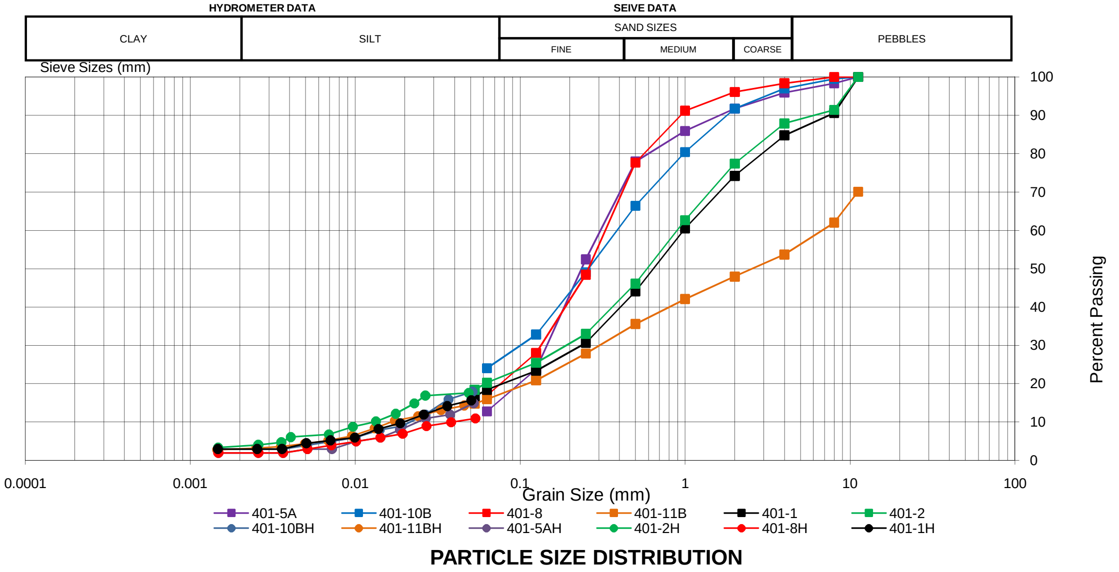
$$K = \frac{g}{v} \times 1x10^{-2} n^{3.287} d_{10}^{2} \qquad \text{(A.4)}$$

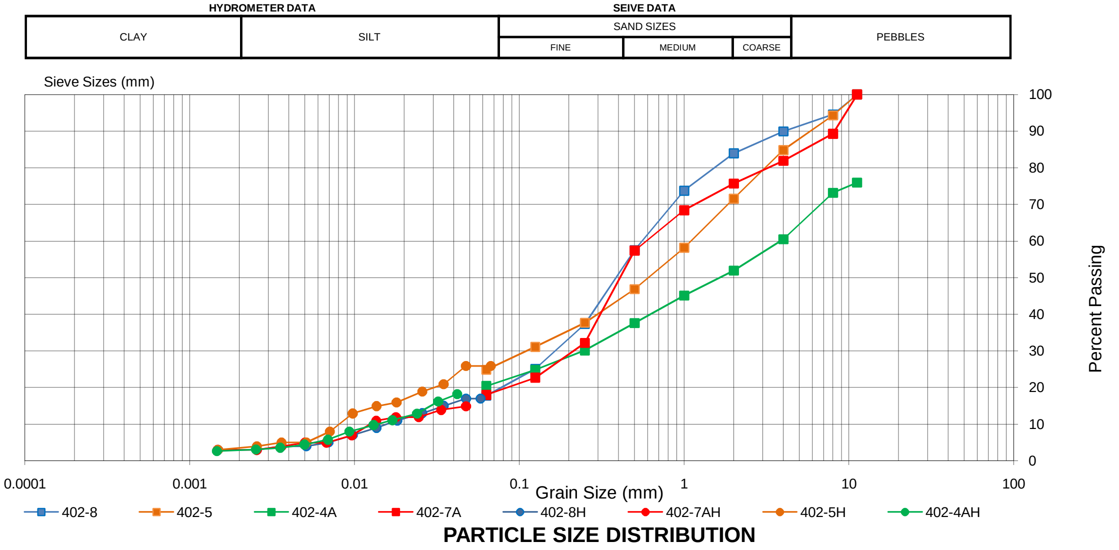
The Kozeny-Carman approach was also used and is applicable for sediments whose effective grain size, d_{10} is greater than 3 mm or does not consist of clay-rich soils (Carrier, 2003) where the hydraulic conductivity is calculated from Equation (A.5):

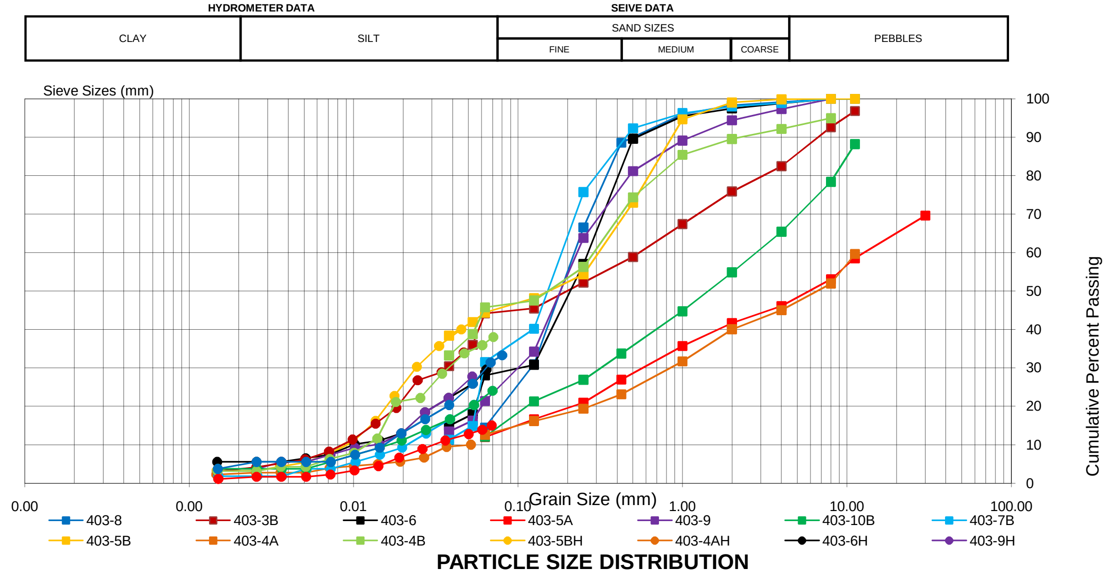
$$K = \frac{g}{v} \times 8.3x10^{-3} \left[\frac{n^3}{(1-n)^2}\right] d_{10}^{2} \qquad \text{(A.5)}$$

The Schlichter and Kozeny-Carman empirical methods were selected as part of estimating the vertical distribution of hydraulic conductivity in the subsurface based on formulae yielding similar results to more appropriate falling head permeameter testing conducted on select soil samples. The hydraulic conductivity of each soil sample was taken to be the Kozeny-Carman value and when appropriate the arithmetic average between both empirical methods was used.

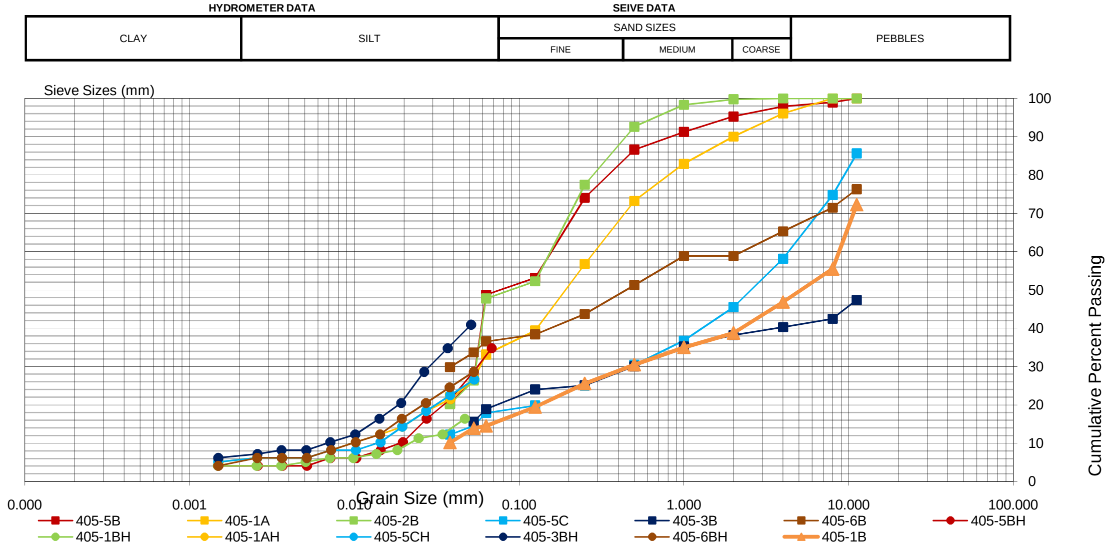
Grain size distribution of sediment samples collected from boreholes BH-401, BH-402 and BH-403 requiring hydrometer testing.



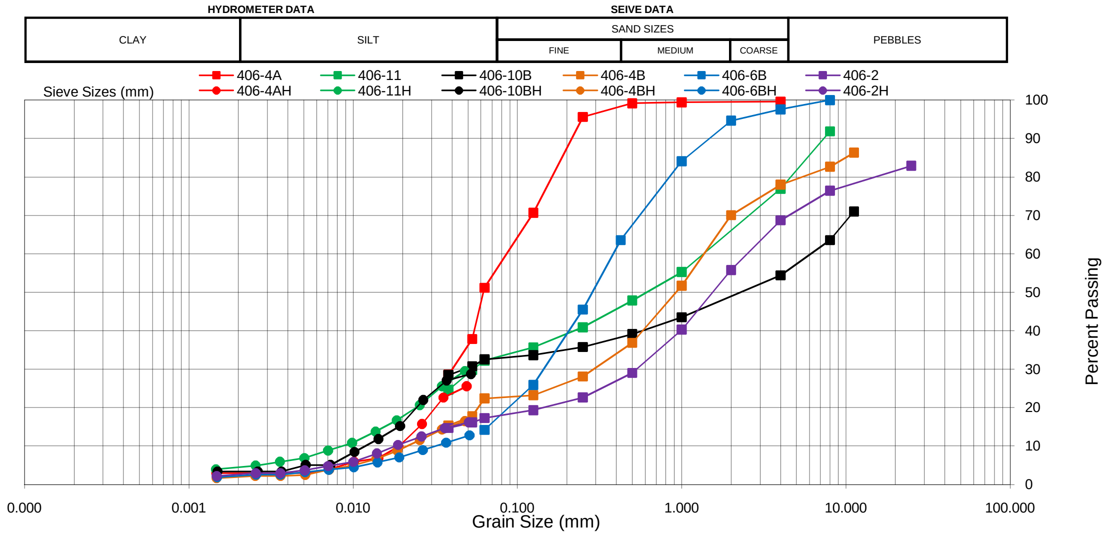




Grain size distribution of sediment samples collected from boreholes BH-405, BH-406 and BH-501 requiring hydrometer testing.



PARTICLE SIZE DISTRIBUTION



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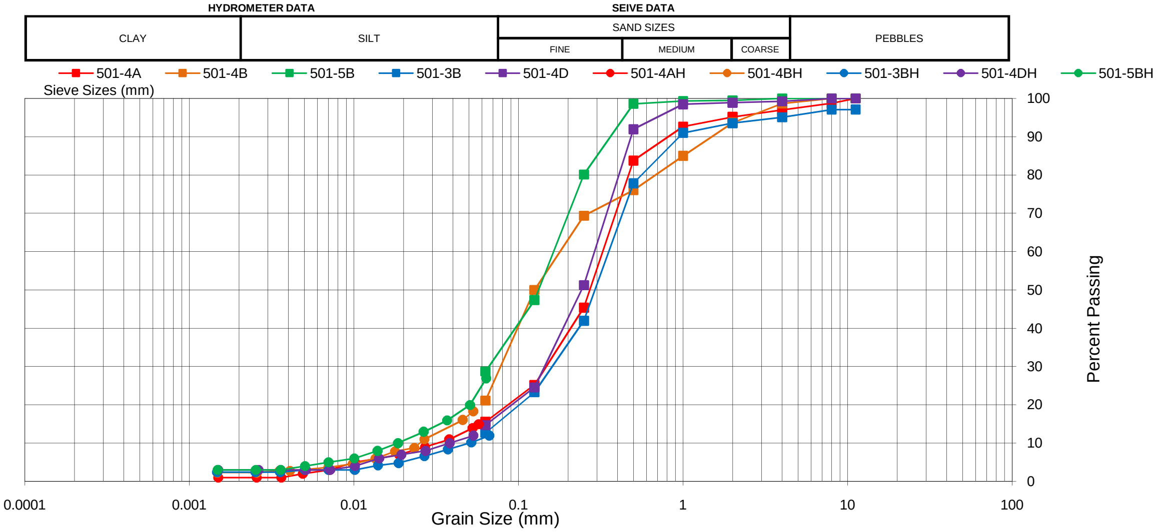
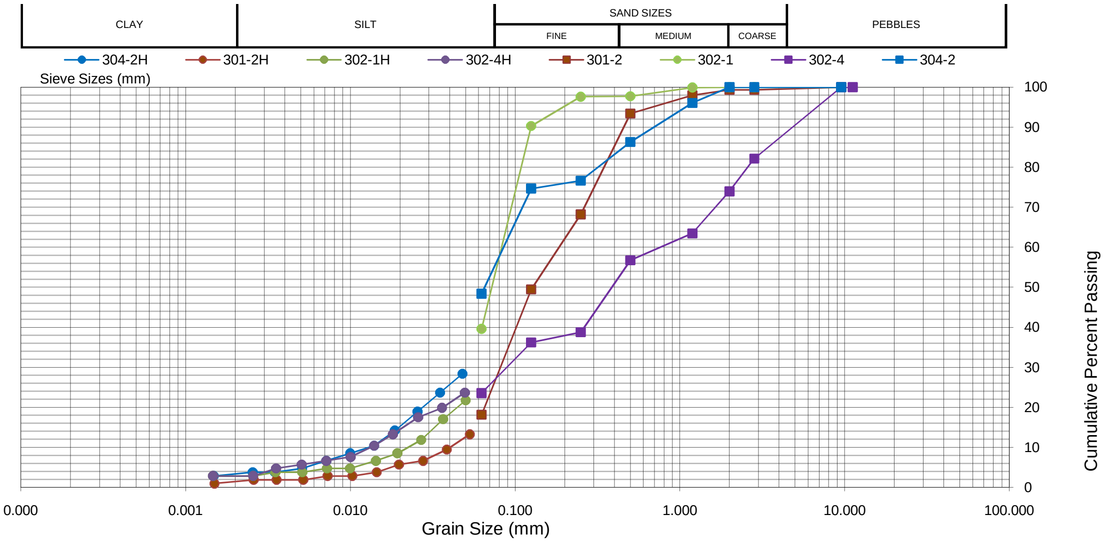


ICLE SIZE DISTRIBUTION

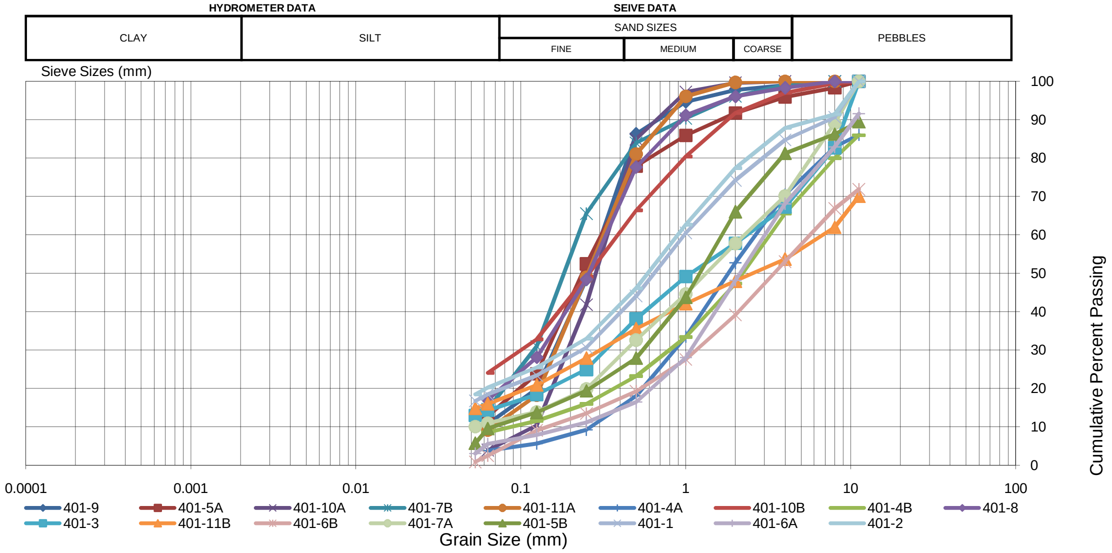
Grain size distribution of sediment samples collected from boreholes BH-301, BH-302 and BH-304 requiring hydrometer testing.

HYDROMETER DATA SEIVE DATA



PARTICLE SIZE DISTRIBUTION

Grain size distribution of sediment samples collected from borehole BH-401.



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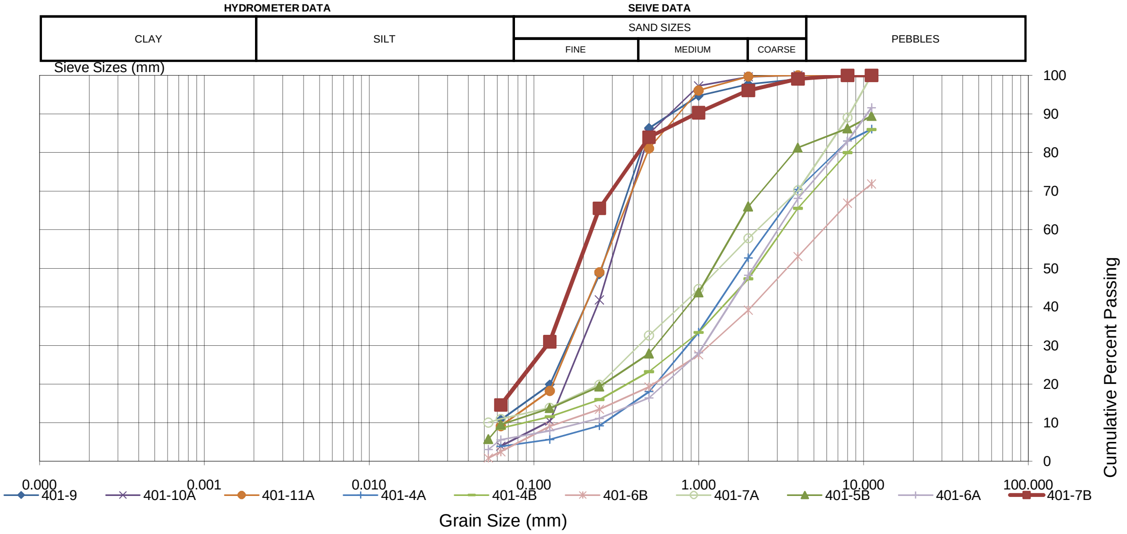

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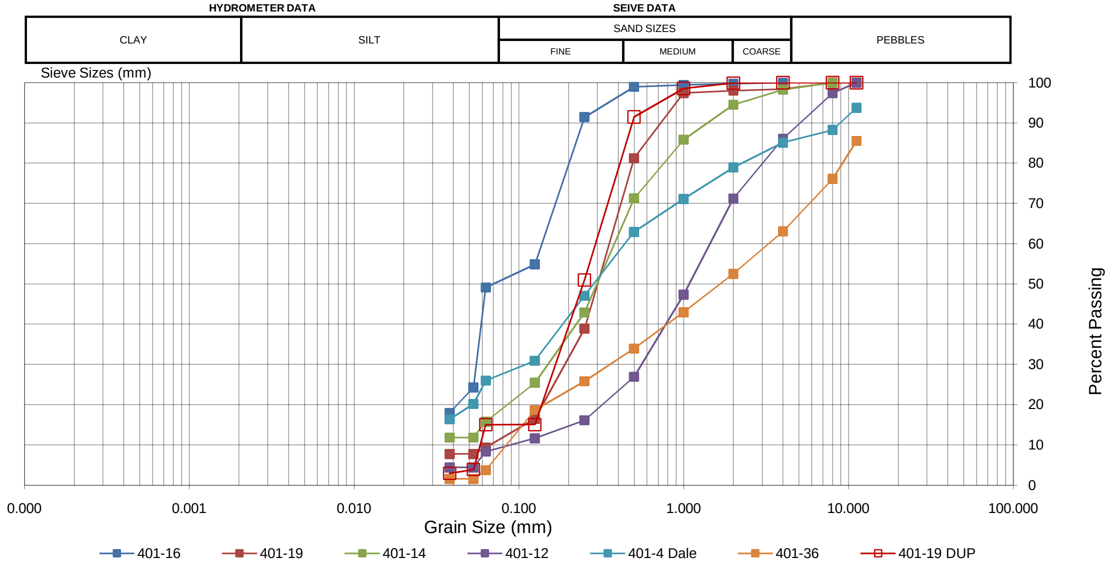
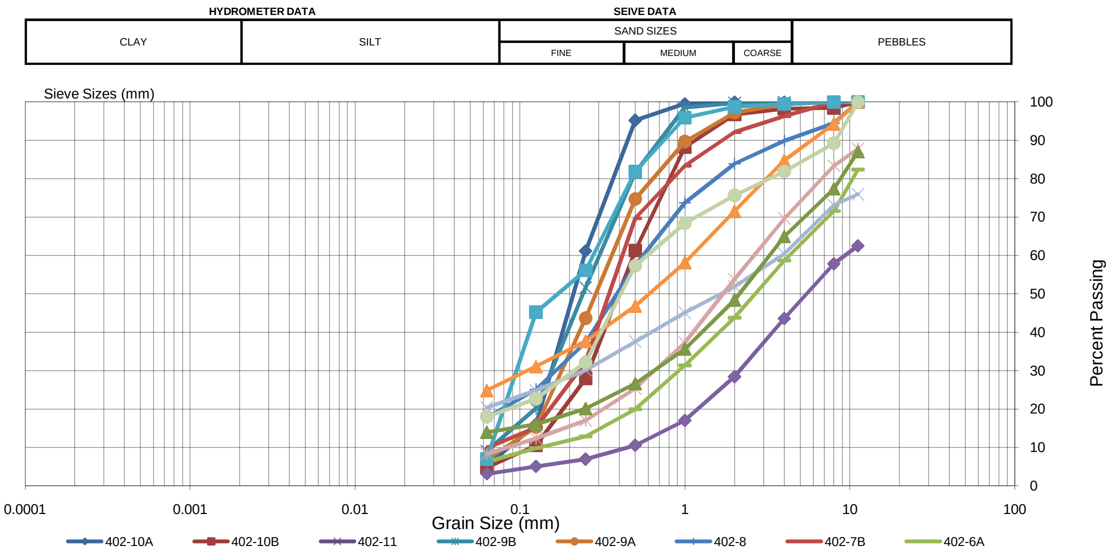
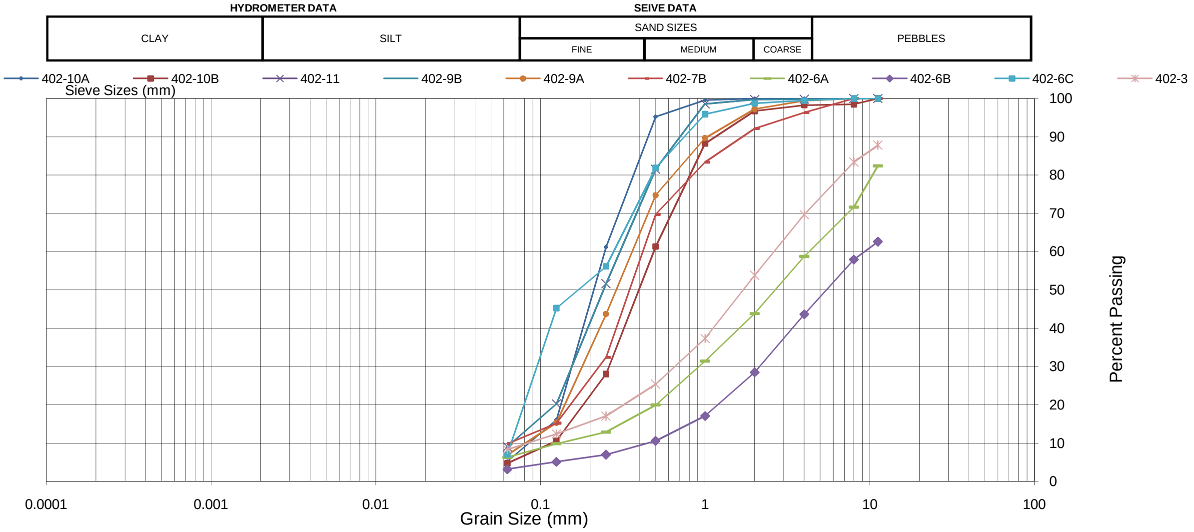


PARTICLE SIZE DISTRIBUTION

Grain size distribution of sediment samples collected from borehole BH-402.



PARTICLE SIZE DISTRIBUTION



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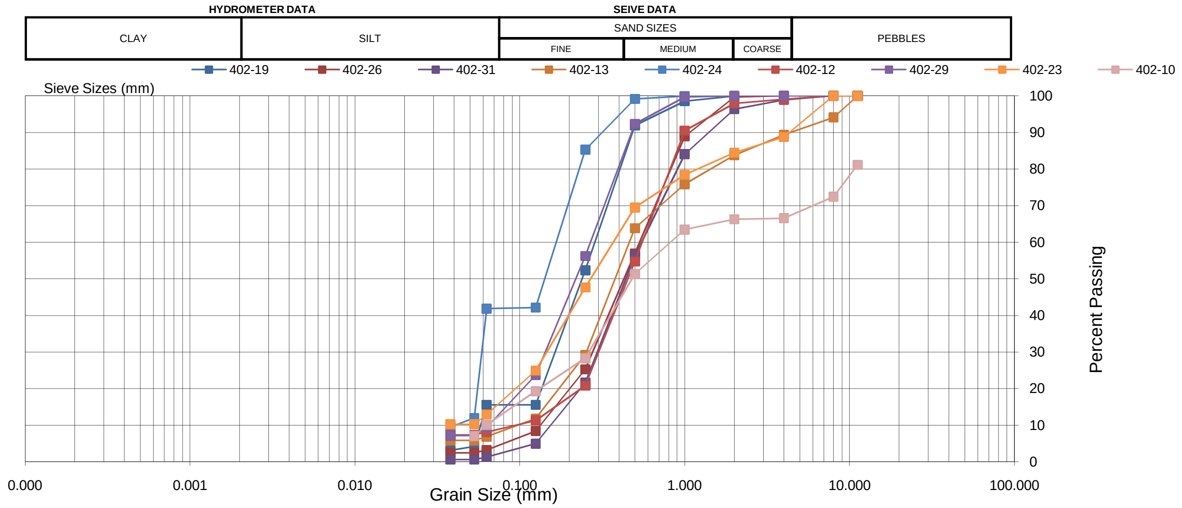
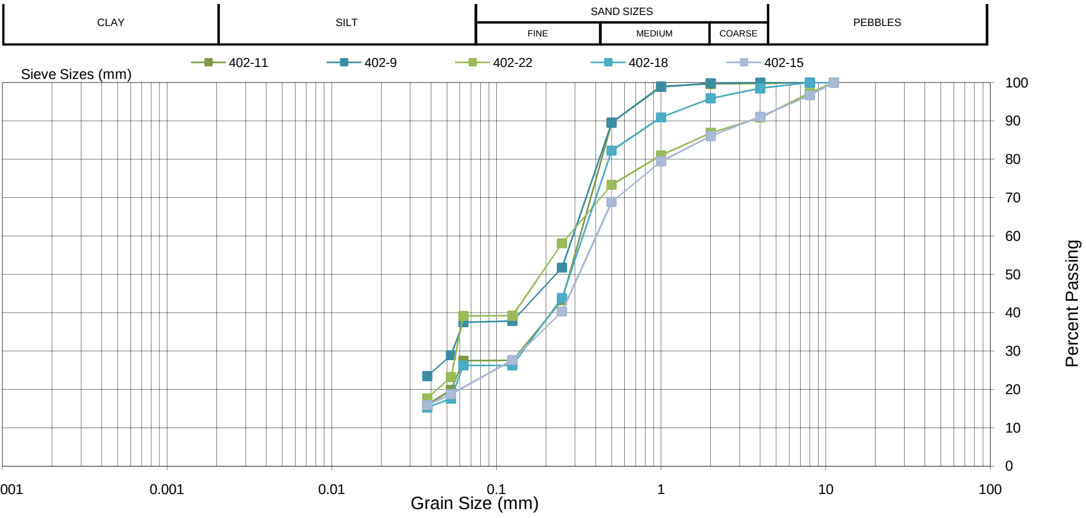
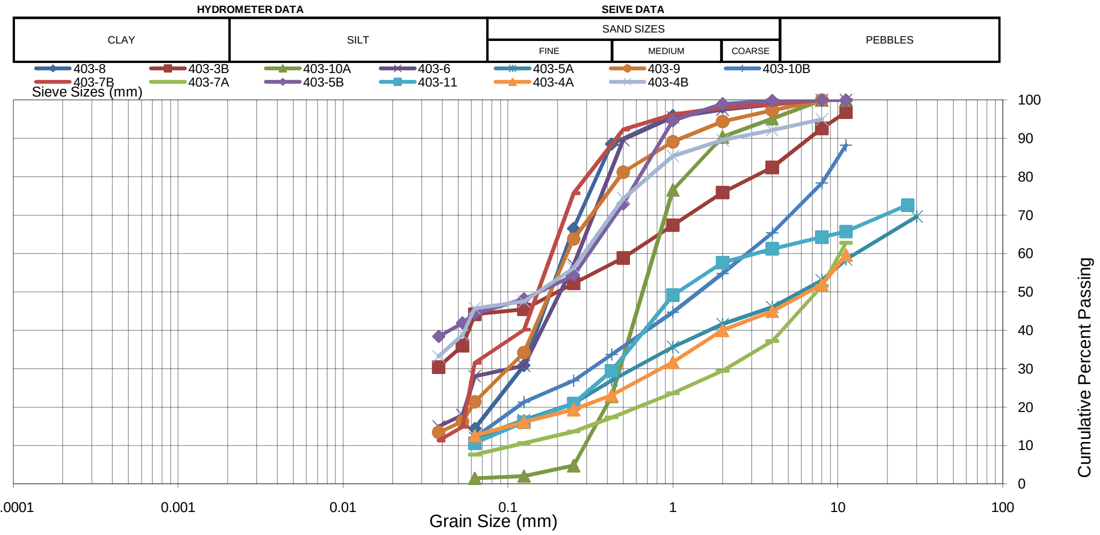


PARTICLE SIZE DISTRIBUTION

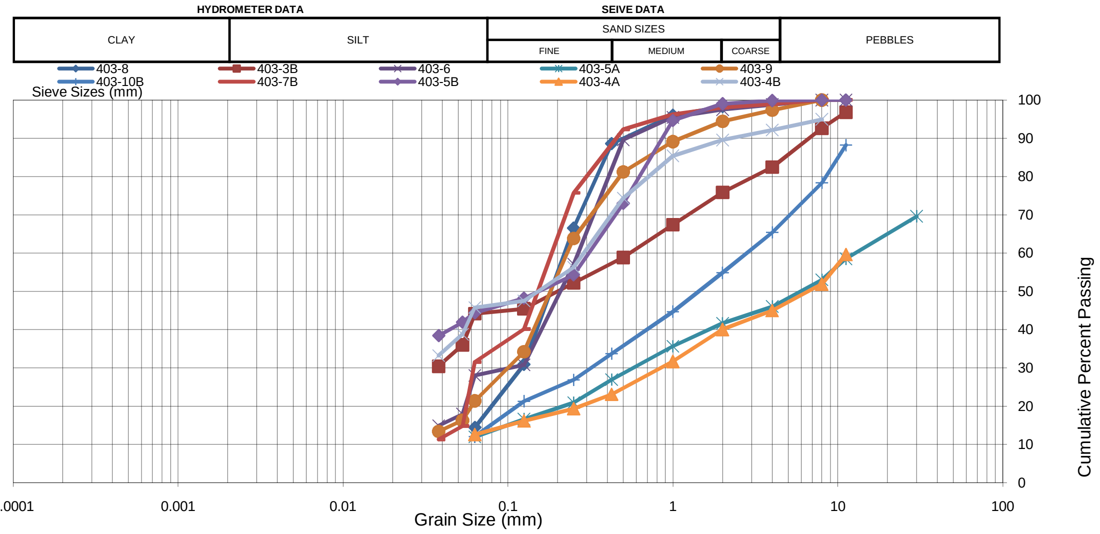
Grain size distribution of sediment samples collected from boreholes BH-402 and BH-403.



PARTICLE SIZE DISTRIBUTION

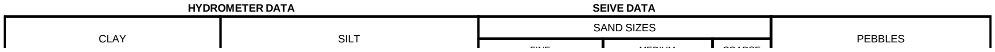


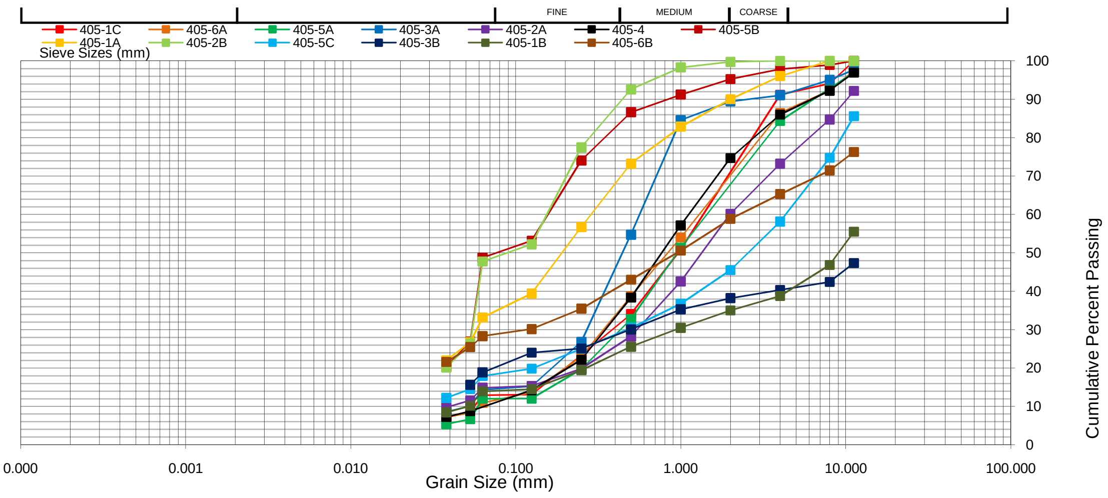
PARTICLE SIZE DISTRIBUTION



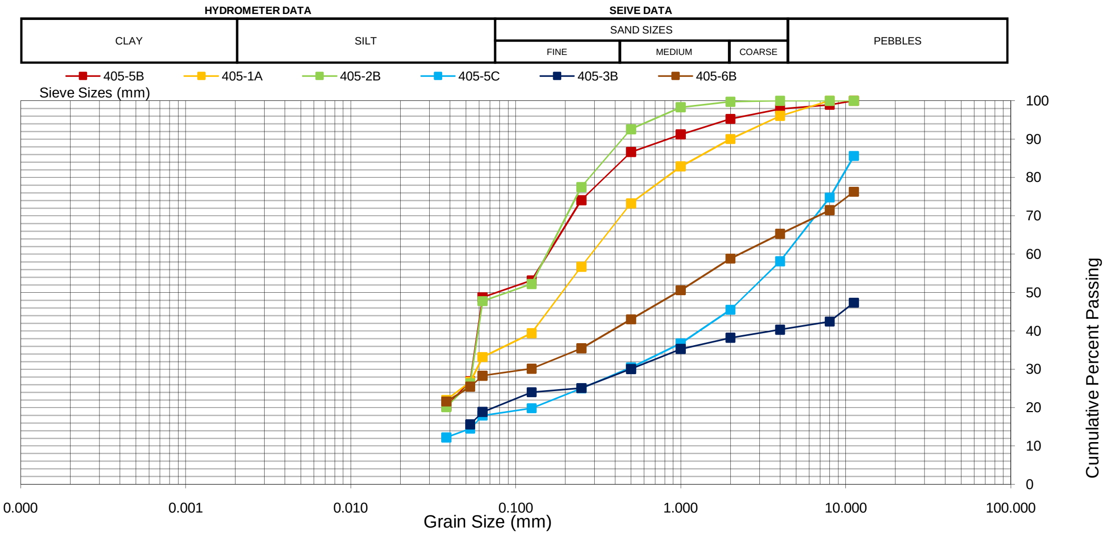
PARTICLE SIZE DISTRIBUTION

Grain size distribution of sediment samples collected from borehole BH-405.



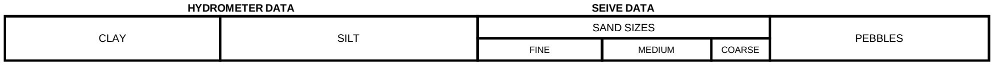


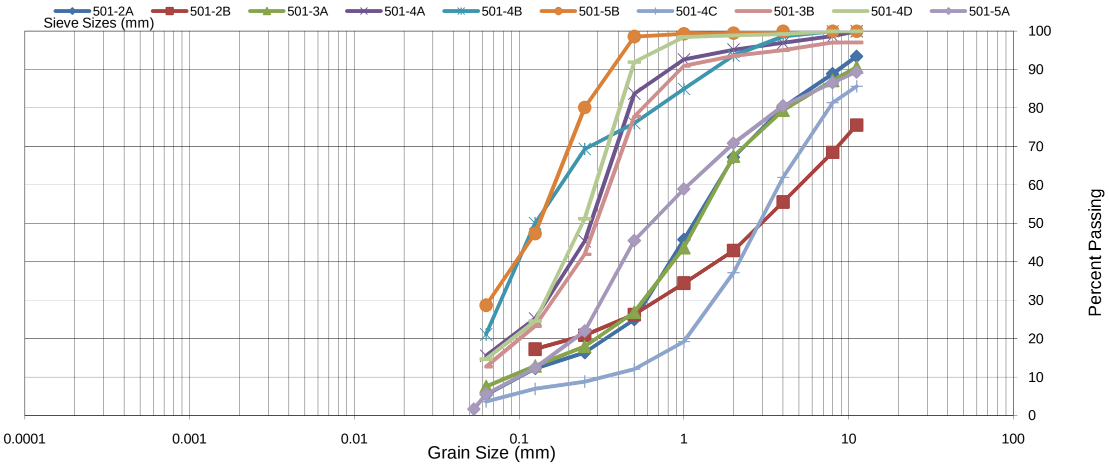
PARTICLE SIZE DISTRIBUTION



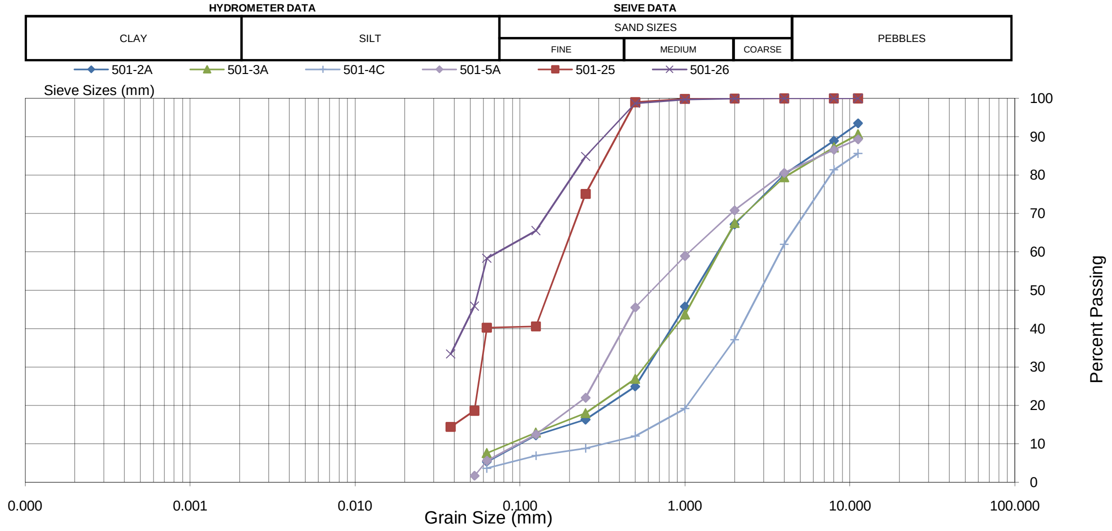
PARTICLE SIZE DISTRIBUTION

Grain size distribution of sediment samples collected from borehole BH-501





PARTICLE SIZE DISTRIBUTION



PARTICLE SIZE DISTRIBUTION

Table A.9 Summary of grain size analysis results and sediment descriptions.

Sample ID	Elevation (m AMSL)	Hazen K (m/s)	Beyer K (m/s)	Schlitchter K (m/s)	Kozeny-Carmen K (m/s)	Average Kozeny-Carmen & Slitcher K (m/s)	Sediment Description	n	% mud	% sand	% gravel	d_{10}	d_{60}	U
401-1	309.20	3.4E-06	1.8E-06	5.7E-07	1.4E-06	9.9E-07	SAND and GRAVEL with some silt	0.35	14%	44%	42%	0.02	1.0	50
401-2	308.44	1.3E-06	9.3E-07	3.2E-07	7.7E-07	5.5E-07	SAND with some silt and gravel	0.29	20%	57%	23%	0.02	0.9	60
401-3	307.67	2.0E-06	1.1E-06	5.7E-07	1.4E-06	9.9E-07	gravelly SAND with some silt	0.27	19%	56%	26%	0.02	2.5	125
401-4A	307.09	4.7E-04	4.8E-04	9.0E-05	2.1E-04	1.5E-04	SAND and GRAVEL with some silt	0.33	4%	49%	47%	0.25	2.5	10
401-4B	306.71	5.8E-05	4.1E-05	1.2E-05	2.8E-05	2.0E-05	sandy GRAVEL with trace silt	-	8%	39%	53%	0.09	3.4	38
401-5A	306.32	4.4E-06	4.6E-06	9.0E-07	2.1E-06	1.5E-06	SAND with some silt and trace gravel	-	13%	79%	8%	0.03	0.3	12
401-5B	305.94	3.5E-03	5.1E-03	7.0E-04	1.7E-03	1.2E-03	gravelly SAND with trace silt	-	9%	57%	34%	0.70	1.7	2
401-6A	305.62	2.9E-04	2.7E-04	5.7E-05	1.4E-04	9.9E-05	sandy GRAVEL with trace silt	-	5%	43%	52%	0.20	3.0	15
401-6B	305.24	7.9E-05	4.9E-05	1.6E-05	3.8E-05	2.7E-05	sandy GRAVEL with trace silt	-	2%	37%	61%	0.11	5.5	52
401-7A	304.63	2.2E-03	2.8E-03	4.3E-04	1.0E-03	7.2E-04	SAND and GRAVEL with some silt	-	11%	47%	42%	0.55	2.5	5
401-7B	304.63	1.8E-05	2.3E-05	3.6E-06	8.6E-06	6.1E-06	SAND with some silt and trace gravel	-	15%	82%	4%	0.05	0.2	5
401-8	303.86	6.5E-06	6.7E-06	1.3E-06	3.1E-06	2.2E-06	SAND with some silt and trace gravel	-	17%	79%	4%	0.03	0.3	11
401-9	303.10	2.6E-05	3.1E-05	5.2E-06	1.2E-05	8.6E-06	SAND with trace silt and gravel	-	11%	87%	2%	0.06	0.4	6
401-10A	302.42	7.9E-05	1.1E-04	1.6E-05	3.8E-05	2.7E-05	SAND with trace silt and gravel	-	4%	96%	0%	0.11	0.4	3
401-10B	302.04	2.1E-06	2.5E-06	5.7E-07	1.4E-06	9.9E-07	silty SAND and trace gravel	0.28	24%	68%	8%	0.02	0.4	20
401-11A	301.65	3.5E-05	4.4E-05	7.0E-06	1.7E-05	1.2E-05	SAND with trace silt and gravel	-	9%	91%	0%	0.07	0.4	5
401-11B	301.27	1.3E-06	1.6E-07	4.6E-07	1.1E-06	7.8E-07	sandy GRAVEL with some silt	0.25	16%	32%	52%	0.02	7.0	389
402-3	307.66	5.2E-05	-	1.0E-05	2.5E-05	1.8E-05	SAND and GRAVEL with trace silt	-	8%	46%	46%	0.09	2.5	29
402-4	306.90	1.6E-06	-	3.2E-07	7.7E-07	5.5E-07	sandy silty GRAVEL	-	20%	32%	48%	0.02	4.0	267
402-5	306.14	4.6E-07	-	9.2E-08	2.2E-07	1.6E-07	gravelly silty SAND	-	25%	47%	29%	0.01	1.1	138
402-6A	305.62	1.6E-04	-	3.2E-05	7.7E-05	5.5E-05	GRAVEL and SAND with trace silt	-	6%	38%	56%	0.15	4.5	30
402-6B	305.36	1.5E-03	-	2.9E-04	7.0E-04	5.0E-04	sandy GRAVEL with trace silt	0.33	4%	25%	71%	0.45	9.0	20
402-6C	305.11	3.0E-05	-	6.1E-06	1.5E-05	1.1E-05	SAND with trace silt	-	6%	93%	1%	0.07	0.3	4
402-7A	304.91	1.5E-06	-	3.2E-07	7.7E-07	5.5E-07	gravelly SAND with some silt	0.31	18%	58%	24%	0.02	4.0	267
402-7B	304.52	3.5E-05	-	7.0E-06	1.7E-05	1.2E-05	SAND with trace silt and gravel	-	9%	83%	8%	0.07	0.4	6
402-8	303.85	1.3E-06	-	3.2E-07	7.7E-07	5.5E-07	SAND with some gravel and silt	0.29	17%	67%	16%	0.02	0.6	37
402-9A	303.24	5.9E-05	-	9.2E-06	2.2E-05	1.6E-05	SAND with trace gravel and silt	0.37	5%	92%	3%	0.08	0.4	4
402-9B	302.86	3.0E-05	-	6.1E-06	1.5E-05	1.1E-05	silty SAND with some gravel	-	19%	67%	14%	0.065	0.3	5
402-10A	302.56	1.6E-04	-	3.2E-05	7.7E-05	5.5E-05	SAND with trace silt	-	5%	95%	0%	0.15	0.3	2
402-10B	302.18	1.4E-04	-	2.8E-05	6.7E-05	4.8E-05	SAND with trace silt and gravel	-	4%	92%	3%	0.14	0.5	4
402-11	301.57	3.0E-05	-	6.1E-06	1.5E-05	1.1E-05	SAND with trace silt	-	7%	92%	0%	0.065	0.3	5
402-31	301.46	2.9E-04	-	3.7E-05	8.8E-05	6.3E-05	SAND with trace silt and gravel	0.41	4%	93%	4%	0.16	0.6	3
403-3B	307.28	5.8E-07	3.3E-07	1.2E-07	2.8E-07	2.0E-07	gravelly SAND with some silt	-	19%	46%	35%	0.01	0.6	61
403-4A	306.93	1.8E-05	3.6E-06	3.6E-06	8.6E-06	6.1E-06	sandy GRAVEL with some silt	-	12%	28%	60%	0.05	12.0	240
403-4B	306.55	1.0E-06	1.2E-06	2.8E-07	6.7E-07	4.8E-07	SILT and SAND with trace gravel	0.28	45%	44%	10%	0.01	0.3	21
403-5A	306.06	6.1E-06	2.5E-07	1.3E-06	3.1E-06	2.2E-06	sandy GRAVEL with some silt	0.31	12%	30%	58%	0.03	13.0	433
403-5B	305.68	6.5E-07	4.9E-07	1.3E-07	3.1E-07	2.2E-07	SILT and SAND	-	44%	55%	1%	0.01	0.3	32
403-6	305.22	7.2E-07	5.9E-07	1.4E-07	3.4E-07	2.4E-07	silty SAND and trace gravel	-	27%	70%	3%	0.01	0.3	25
403-7A	304.54	7.2E-05	3.1E-05	1.4E-05	3.4E-05	2.4E-05	sandy GRAVEL with trace silt	-	7%	22%	71%	0.10	10.0	100
403-7B	304.16	4.0E-06	3.5E-06	6.3E-07	1.5E-06	1.1E-06	silty SAND and trace gravel	0.36	30%	68%	2%	0.02	0.2	9
403-8	303.70	2.0E-06	1.8E-06	3.7E-07	8.8E-07	6.3E-07	SAND with some silt and trace gravel	0.34	14%	84%	2%	0.02	0.2	14
403-9	302.94	1.6E-06	1.3E-06	2.8E-07	6.7E-07	4.8E-07	silty SAND with trace gravel	0.34	21%	74%	6%	0.01	0.2	16
403-10A	302.40	9.7E-04	9.3E-04	1.3E-04	3.1E-04	2.2E-04	SAND with trace gravel and silt	0.40	1%	89%	10%	0.30	0.8	3
403-10B	302.02	6.2E-06	3.7E-06	1.6E-06	3.7E-06	2.7E-06	SAND and GRAVEL with some silt	0.29	12%	43%	45%	0.03	2.9	88
403-11	301.41	2.6E-05	1.6E-05	5.2E-06	1.2E-05	8.6E-06	SAND and GRAVEL with some silt	-	10%	47%	42%	0.06	3.0	50
405-1A	306.27	7.8E-07	5.6E-07	1.4E-07	3.4E-07	2.4E-07	silty SAND with trace gravel	0.33	37%	53%	9%	0.01	0.3	29
405-1B	305.98	1.7E-06	8.2E-08	5.7E-07	1.4E-06	9.9E-07	silty GRAVEL with some sand	0.25	29%	17%	53%	0.02	9.0	450

Table A.9 Summary of grain size analysis results and sediment descriptions.

Sample ID	Elevation (m AMSL)	Hazen K (m/s)	Beyer K (m/s)	Schlitchter K (m/s)	Kozeny-Carmen K (m/s)	Average Kozeny-Carmen & Slitcher K (m/s)	Sediment Description	n	% mud	% sand	% gravel	d_{10}	d_{60}	U
405-1C	305.67	1.4E-05	1.7E-05	4.3E-06	1.0E-05	7.2E-06	SAND with some silt and trace gravel	0.27	18%	74%	8%	0.06	1.5	26
405-2A	305.38	9.2E-06	7.2E-06	2.3E-06	5.5E-06	3.9E-06	SAND with silt and gravel	0.29	35%	35%	31%	0.04	2.0	50
405-2B	305.00	7.2E-07	6.7E-07	1.4E-07	3.4E-07	2.4E-07	SILT and SAND	-	46%	54%	0%	0.01	0.2	16
405-3A	304.53	2.3E-05	2.3E-05	4.3E-06	1.0E-05	7.2E-06	SAND with some silt and trace gravel	0.33	14%	76%	11%	0.06	0.6	10
405-3B	304.15	2.0E-05	1.2E-05	7.0E-06	1.7E-05	1.2E-05	sandy GRAVEL and silt	0.25	36%	26%	38%	0.07	10.0	143
405-4	303.68	2.6E-05	3.0E-05	6.6E-06	1.6E-05	1.1E-05	GRAVEL and SAND with trace silt	0.28	7%	36%	57%	0.07	1.2	18
405-5A	303.11	2.2E-05	2.1E-05	5.2E-06	1.2E-05	8.6E-06	SAND with some gravel and silt	0.29	11%	73%	16%	0.06	1.6	26
405-5B	302.82	3.1E-06	3.2E-06	5.7E-07	1.4E-06	9.9E-07	SILT and SAND with trace gravel	0.33	47%	48%	5%	0.02	0.2	8
405-5C	302.62	1.6E-06	2.6E-07	3.2E-07	7.7E-07	5.5E-07	sandy GRAVEL with some silt	-	17%	28%	55%	0.02	4.2	280
405-6A	302.42	2.6E-05	2.2E-05	5.2E-06	1.2E-05	8.6E-06	SAND with some silt and gravel	-	11%	76%	14%	0.06	1.4	23
405-6B	302.04	7.4E-07	1.4E-07	1.4E-07	3.4E-07	2.4E-07	sandy silty GRAVEL	0.32	28%	31%	41%	0.01	2.5	250
406-2	308.24	2.9E-06	1.1E-06	5.7E-07	1.4E-06	9.9E-07	sandy GRAVEL with some silt	-	20%	37%	43%	0.02	2.6	130
406-4A	307.48	2.9E-06	1.9E-06	5.7E-07	1.4E-06	9.9E-07	sandy SILT	-	66%	33%	0%	0.02	0.9	45
406-4B	306.95	5.2E-05	4.7E-05	1.0E-05	2.5E-05	1.8E-05	gravelly silty SAND	-	25%	46%	29%	0.09	1.5	18
406-5	306.57	6.4E-06	2.0E-06	2.2E-06	5.2E-06	3.7E-06	silty sandy GRAVEL	0.25	27%	20%	53%	0.04	10.1	259
406-6A	305.96	7.7E-05	3.3E-05	8.1E-06	1.9E-05	1.4E-05	SAND and GRAVEL with trace silt	0.47	7%	56%	37%	0.08	1.8	24
406-6B	305.42	6.0E-06	7.4E-06	1.5E-06	3.5E-06	2.5E-06	SAND with some silt and trace gravel	0.29	14%	81%	5%	0.03	0.4	13
406-7A	305.04	6.7E-05	6.3E-05	1.0E-05	2.5E-05	1.8E-05	SAND with trace silt and gravel	0.37	7%	91%	2%	0.09	0.5	6
406-7B	304.54	1.2E-05	2.2E-06	2.3E-06	5.5E-06	3.9E-06	sandy GRAVEL with some silt	0.32	14%	26%	61%	0.04	10.0	250
406-8	304.16	1.2E-04	1.0E-04	2.4E-05	5.8E-05	4.1E-05	SAND and GRAVEL	0.31	4%	48%	48%	0.13	3.0	23
406-9A	303.67	4.5E-04	5.7E-04	9.0E-05	2.1E-04	1.5E-04	SAND with trace gravel and silt	-	2%	92%	5%	0.25	1.2	5
406-9B	303.06	9.8E-06	1.5E-05	3.6E-06	8.6E-06	6.1E-06	gravelly SAND with some silt	0.25	12%	57%	31%	0.05	1.2	24
406-10A	302.68	7.2E-03	7.5E-03	1.4E-03	3.4E-03	2.4E-03	GRAVEL with some sand and trace silt	-	6%	11%	84%	1.00	10.7	11
406-10B	302.22	1.0E-06	6.5E-07	2.1E-07	4.9E-07	3.5E-07	silty GRAVEL with some sand	0.31	32%	11%	57%	0.01	0.6	50
406-11	301.84	1.7E-06	1.1E-06	5.7E-07	1.4E-06	9.9E-07	silty sandy GRAVEL	0.25	32%	23%	45%	0.02	2.6	130
501-2A	305.68	7.2E-05	6.9E-05	1.4E-05	3.4E-05	2.4E-05	gravelly SAND with trace silt	-	9%	59%	32%	0.10	1.5	15
501-2B	305.30	5.8E-05	5.4E-05	1.2E-05	2.8E-05	2.0E-05	sandy GRAVEL with some silt	-	19%	34%	46%	0.09	1.5	17
501-3A	304.79	5.2E-05	4.7E-05	1.0E-05	2.5E-05	1.8E-05	gravelly SAND with trace silt	-	11%	58%	31%	0.09	1.5	18
501-3B	304.40	1.5E-05	2.1E-05	3.6E-06	8.6E-06	6.1E-06	silty SAND with trace gravel	0.30	24%	70%	6%	0.05	0.4	7
501-4A	304.13	5.4E-06	7.2E-06	1.3E-06	3.1E-06	2.2E-06	SAND with some silt and trace gravel	0.29	17%	79%	5%	0.03	0.3	8
501-4B	303.90	5.1E-06	5.2E-06	9.0E-07	2.1E-06	1.5E-06	silty SAND with trace gravel	0.34	22%	72%	6%	0.03	0.2	7
501-4C	303.73	6.5E-04	6.5E-04	1.3E-04	3.1E-04	2.2E-04	sandy GRAVEL with trace silt	-	4%	34%	63%	0.30	3.8	13
501-4D	303.58	1.2E-05	1.3E-05	2.3E-06	5.5E-06	3.9E-06	SAND with some silt and trace gravel	-	14%	85%	1%	0.04	0.3	8
501-5A	303.34	4.9E-05	6.5E-05	1.3E-05	3.1E-05	2.2E-05	gravelly SAND with trace silt	0.28	8%	63%	28%	0.10	1.2	13
501-25	302.97	1.5E-05	1.9E-05	2.9E-06	7.0E-06	5.0E-06	silty SAND	0.01	39%	61%	0%	0.05	0.2	4
501-5B	302.96	4.7E-06	3.1E-06	5.7E-07	1.4E-06	9.9E-07	silty SAND	0.42	28%	71%	0%	0.02	0.2	9
501-26	302.87	9.7E-06	7.4E-06	1.0E-06	2.5E-06	1.8E-06	SAND and SILT	0.46	57%	43%	0%	0.03	0.1	3

Notes

Unit 1	FILL
Unit 2	SAND
Unit 3	SAND and GRAVEL
Unit 4	SAND
Unit 5	SAND and GRAVEL
Unit 6	SAND

n - porosity

d_{10} - effective grain size diameter where 10% are finer

d_{60} effective grain size diameter where 60% are finer

U uniformity coefficient, $U = d_{60}/d_{10}$

\- no data

where variance log cycles is equivalent to the total sum of the differences between log K and the average log K.

heterogeneity is inferred when variance log cycle exceeds 0.5.

Borehole	Variance	Variance log cycles
BH-401	1.1E-07	0.95
BH-402	1.5E-08	0.81
BH-403	3.6E-09	0.91
BH-405	2.0E-11	0.69
BH-406	4.1E-07	1.05
BH-501	3.8E-09	5.01

Table A.11 Summary of the falling-head permeamebter test results of select sediment samples.

Sample ID	**Sediment Description**	**L cm**	**Manometer**	**Trial**	**Initial Height**	**Final Height**	**Height Difference**	**a * L manometer cm^2**	**Time s**	**K m/s**	**Average K m/s**
301-2	SAND with some silt	2.6	2	1	1.15	0.95	20	1.9	49.83	1.3E-04	
				2	1.15	0.95	20	1.9	48.41	1.3E-04	
				3	1.15	0.95	20	1.9	49.4	1.3E-04	
				4	1.15	0.95	20	1.9	49.13	1.3E-04	
				5	1.15	0.95	20	1.9	49.36	1.3E-04	1.3E-04
304-2	silty SAND with some gravel	2.6	3	1	1.15	0.95	20	1.9	43.57	1.5E-04	
				2	1.15	0.95	20	1.9	43.6	1.5E-04	
				3	1.15	0.95	20	1.9	44	1.5E-04	
				4	1.15	0.95	20	1.9	44.13	1.5E-04	
				5	1.15	0.95	20	1.9	44.14	1.5E-04	1.5E-04
302-2	SAND with trace silt and gravel	2.6	1	1	1.15	0.95	20	1.9	36.58	1.8E-04	
				2	1.15	0.95	20	1.9	35.49	1.8E-04	
				3	1.15	0.95	20	1.9	35.39	1.8E-04	
				4	1.15	0.95	20	1.9	36.06	1.8E-04	
				5	1.15	0.95	20	1.9	36.31	1.8E-04	1.8E-04
302-1	silty SAND	3	2	1	1.05	0.95	10	1.9	203.53	8.4E-06	
				2	1.05	0.95	10	1.9	203.23	8.4E-06	
				3	1.05	0.95	10	1.9	203.31	8.4E-06	
				4	1.05	0.95	10	1.9	202.28	8.4E-06	
				5	1.05	0.95	10	1.9	202.87	8.4E-06	
				6	1.05	0.95	10	1.9	202.74	8.4E-06	
				7	1.05	0.95	10	1.9	203.21	8.4E-06	
				8	1.05	0.95	10	1.9	203.88	8.3E-06	8.4E-06
302-4	gravelly silty SAND	3.2	1	1	1.15	0.95	20	7.8	21.7	1.2E-03	
				2	1.15	0.95	20	7.8	20.09	1.3E-03	
				3	1.15	0.95	20	7.8	20.44	1.3E-03	1.2E-03
301-1	SAND with some gravel and trace silt	2.6	1	1	1.15	0.95	20	7.8	38.84	6.7E-04	
				2	1.15	0.95	20	7.8	33.53	7.7E-04	
				3	1.15	0.95	20	7.8	31.57	8.2E-04	
				4	1.15	0.95	20	7.8	30.13	8.6E-04	
				5	1.15	0.95	20	7.8	29.98	8.6E-04	
				6	1.15	0.95	20	7.8	29.59	8.7E-04	
				7	1.15	0.95	20	7.8	29.72	8.7E-04	
				8	1.15	0.95	20	7.8	30.87	8.4E-04	
				9	1.15	0.95	20	7.8	31.81	8.1E-04	
				10	1.15	0.95	20	7.8	34.18	7.6E-04	
				11	1.15	0.95	20	7.8	39.5	6.6E-04	8.0E-04
301-4	sandy GRAVEL with trace silt	2.8	1	1	1.05	0.85	20	7.8	21.93	1.3E-03	
				2	1.05	0.85	20	7.8	20.03	1.4E-03	
				3	1.05	0.85	20	7.8	22.57	1.3E-03	
				4	1.05	0.85	20	7.8	18.91	1.5E-03	
				5	1.05	0.85	20	7.8	29.22	9.8E-04	1.3E-03
301-3	GRAVEL with some sand and trace silt	2.8	1	1	1.05	0.85	20	7.8	18.79	1.5E-03	
				2	1.05	0.85	20	7.8	23.5	1.2E-03	
				3	1.05	0.85	20	7.8	13.19	2.2E-03	
				4	1.05	0.85	20	7.8	20.13	1.4E-03	1.6E-03
302-3	GRAVEL and SAND with trace silt	2.8	1	1	1.05	0.85	20	7.8	106.78	2.7E-04	
				2	1.05	0.85	20	7.8	23.97	1.2E-03	
				3	1.05	0.85	20	7.8	32.94	8.7E-04	
				4	1.05	0.85	20	7.8	23.31	1.2E-03	
				5	1.05	0.95	10	7.8	51.94	1.3E-04	
				6	1.05	0.85	20	7.8	41.69	6.9E-04	7.3E-04
401-19	SAND with trace silt and gravel	3.8	2	1	1.25	0.95	30	1.9	30.25	4.6E-04	
				2	1.25	0.95	30	1.9	29.7	4.7E-04	
				3	1.25	0.95	30	1.9	28.18	5.0E-04	4.8E-04
405-5B	SILT and SAND with trace gravel	4.8	2	1	1.15	1.05	10	1.9	248	6.2E-06	
				2	1.05	0.95	10	1.9	274	6.2E-06	
				3	0.95	0.85	10	1.9	305	6.2E-06	6.2E-06
406-7A	SAND with trace silt and gravel	5	2	1	1.15	0.95	20	1.9	34.69	1.9E-04	
				2	1.05	0.85	20	1.9	41.35	1.7E-04	
				3	1.05	0.85	20	1.9	42.17	1.7E-04	1.8E-04
403-9	silty SAND with trace gravel	4.4	2	1	1.15	1.05	10	1.9	153.55	1.0E-05	
				2	1.05	0.95	10	1.9	169.93	1.0E-05	
				3	0.95	0.85	10	1.9	191.42	9.9E-06	1.0E-05

Table A.11 Summary of the falling-head permeamebter test results of select sediment samples.

Sample ID	**Sediment Description**	**L cm**	**Manometer**	**Trial**	**Initial Height**	**Final Height**	**Height Difference**	**a * L manometer cm^2**	**Time s**	**K m/s**	**Average K m/s**
402-7A	gravelly SAND with some silt	3	2	1	1.15	1.025	12.5	1.9	636	3.8E-06	
				2	1.03	0.95	7.5	1.9	570	1.7E-06	
				3	0.95	0.846	10.4	1.9	758	2.7E-06	2.7E-06
403-10A	SAND with trace gravel and silt	4.2	2	1	1.45	0.85	60	1.9	13.71	4.0E-03	
				2	1.25	0.85	40	1.9	11.52	2.3E-03	
				3	1.25	0.85	40	1.9	11.39	2.3E-03	2.8E-03
403-10A	SAND with trace gravel and silt	4.2	1	1	1.15	0.85	30	7.8	27.26	2.3E-03	
				2	1.05	0.85	20	7.8	27.18	1.1E-03	
				3	1.05	0.85	20	7.8	27.3	1.0E-03	1.5E-03
402-9A	SAND with trace gravel and silt	4.7	1	1	1.15	0.95	20	7.8	118.88	2.2E-04	
				2	1.15	0.95	20	7.8	130.2	2.0E-04	
				3	1.15	0.95	20	7.8	120.89	2.1E-04	2.1E-04

A - Cross-sectional area of cylinder = 11.5 cm^2

a - Cross-sectional area of the column which falls from the initial head Ho to Hl during a time interval, t

L - Length of the soil column

Appendix B

Charaterization of Contaminants at the Site including Pre-Injection Soil Coring and Groundwater Sampling Procedures and Results

B.1 Soil Sampling

A standard procedure of the collection of soil samples for the analysis of volatile organic compounds (VOCs) has not yet been established. Barcelona (1989) states that large systematic errors can occur in sample results related to handling and collection procedures more so than sample analysis. The most common discrepancy in measured values of VOCs is the negative bias where results are less than the true value which tends to be difficult to delineate and control (Lewis et al, 1994). The field soil sampling procedure described by Hewitt (1996), Nelson (2007) and Yang (2008) was modified to suit the coring technique used at the Site. The sampling procedure was developed to obtain representative soil samples for VOC analyses while minimizing potential sources of error often encountered during the four stages of the sample collection process as described by Ball (1997): (1) sample collection from subsurface; (2) collection of subsamples from the original sample; (3) sample storage and preservation and (4) extraction and analysis of the VOCs.

Soil core subsamples were collected during two borehole and well drilling programs which occurred November 26-28th and July 13-15th in the vicinity of the expected source zone. Soil cores were collected in 0.75 m increments using a 0.1 m diameter hollow-stem split spoon auger which generated a borehole diameter of 0.21 m. The hollow-stem split spoon technique provides continuous undisturbed soil sampling within the auger drill stem. Split spoons recovered from the auger were left sealed prior to subsample collection in order to minimize the loss of VOCs.

Sand traps were used to mitigate sample loss during the retrieval of the split spoon sampler from the auger casing. Complete split spoon recovery of the sample was achieved 46% of the time based on 114 core recoveries. Sample recovery was 80% or better 59% of the time, 60% or better 75% of the time and the occurrence of no sample recovery were limited to 3 occasions. The low sample recovery in the split spoon auger can be affected by water content, type of material being recovered and obstructions which can impede sample recovery in the auger. No core samples were recovered during the borehole drilling phase of MW-404 due to a cobble that became caught in the auger.

The location of the borehole core recovered corresponds to the objective of determining the types of aquifer materials present and defining the spatial distribution of the source zone through residual soil contamination. Multilevel wells were installed in the borehole locations to determine the relationship between the vertical distribution of residual soil phase and dissolved groundwater phase contamination at discrete intervals in the subsurface. Borehole core subsamples were collected between the depths of 1.5 and 13.4 m bgs in November 2007 and from 1.7 to 9.6 m bgs in July 2009. The location of the soil cores were determined based on historic soil and groundwater records pertaining to the Site. Soil cores were taken in areas of maximum source zone contamination (BH-301, BH-302, BH-303, BH-401, BH-402 and BH-501) and to a lesser extent down gradient of the initial source of contamination (BH-304, BH-403, BH-405 and BH-406).

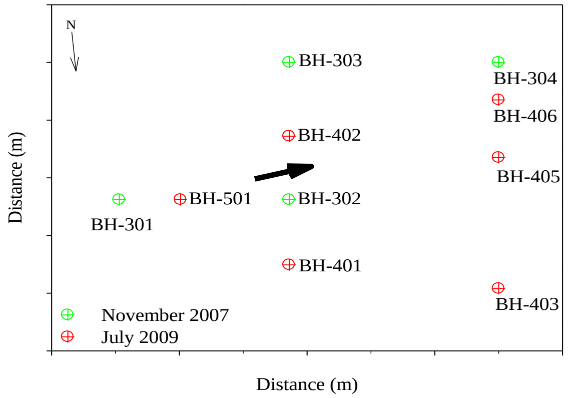


Figure B.1: Plan view r and spatial distribution of residuals in the research area.

The split spoon core was opened and a clean blade (decontaminated with methanol) was used to section off half of the core in parts, exposing a fresh sediment surface for sub sampling while reducing the loss of VOCs to the atmosphere. Approximately 3 mL of soil was collected per sample using a 5 mL plastic syringe which had the tip removed. The syringe containing the subsample was then inserted and deployed into a pre-weighed 20 mL glass vial containing 5 mL of methylene chloride (and internal standard m-fluortoluene (MFT) – 50 u MFT/1000 mL methylene chloride) and quickly caped with a Teflon® lined septum screw-cap lid. The vial containing the subsample was then vigorously shaken for 30 seconds to ensure the soil subsample was well immersed in the methylene chloride in order to dissolve the VOCs. Prepped vials and those containing soil subsamples were kept in a cooler containing ice to minimize the volatilization of the VOCs or methylene chloride through the Teflon® septum. Samples were systematically collected between 10 cm and 35 cm intervals within the core. The variability in sample frequency within the core length corresponded to undesirable material to subsample such as materials with high gravel content and vertical extent of the borehole investigation. The sampling procedure was conducted with the use of 2 workers in order to increase the efficiency of the sample collection. Upon completion of the coring activities, the samples were transported back to Organic Geochemical Laboratory at the University of Waterloo and re-weighed.

A total of 280 samples and 23 field duplicates were collected for extraction analysis of BTEX, TMB and naphthalene. The sampling program in Fall 2007 was conducted at lower sample frequency per borehole core in order to obtain a broader understanding of the residual distribution from 1.5 to 13.4 m bgs, where 110 samples and 9 field duplicates were collected: BH-301 33 samples and 2 field duplicates, BH-302 32 samples and 3 duplicates, BH-303 18 samples and 2 field duplicates and BH-304 27 samples and 2 field duplicates. The sampling program in July 2009 was directed at obtaining a high frequency of samples from residual source zone areas pre-determined by the November 2007 extraction analysis at depths which would be targeted by remediation activities. Soil sampling took place from 1.7 to 9.6 m bgs in July 2009, with a higher frequency of subsample collection occurring 4.5 m bgs to the bottom of the borehole.

After all the subsamples were taken from each split spoon core, the soil samples were collected from the remaining materials for hydraulic conductivity and organic vapour reading measurements.

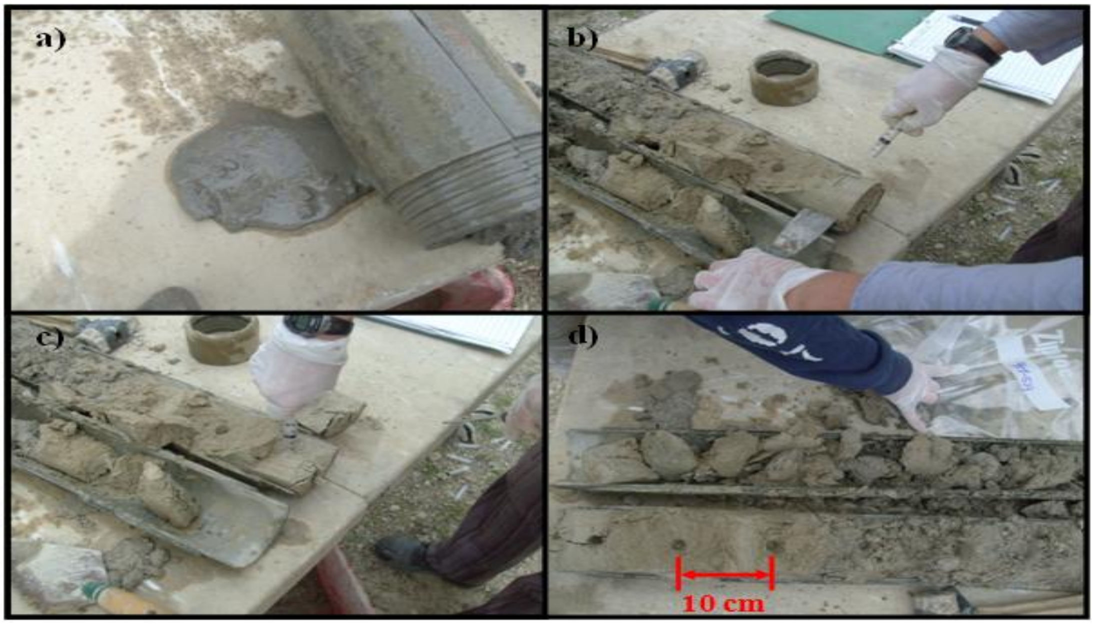


Figure B.2: (a) Split spoon container kept sealed sealed until sampling period. (b) Clean blade used to expose fresh core segment for subsample collection. (c) Syringe inserted into a freshly exposed core segment. (d) Soil subsamples were collected at systematical intervals ranging rom 10 cm to 25 cm depending on the material recovered.

B.2 Soil Chemical Extraction Analysis

All of the laboratory analyses of samples collected in the field were conducted at the Organic Geochemistry Laboratory at the University of Waterloo.

Yang (2008) describes the soil extraction process. Upon arrival to the Laboratory, sample vials were re-weighed and shaken vigorously (350 rpm) for 18 hours in order to further dissolve VOCs in the methylene chloride. Sample vials were re-weighed following the shaking procedure to detect lost solvent in the event the sample vials were not fastened securely. In the event that differences in weight exist between the sample vial before and after the shaking process, the sample was either discarded or weight calculation corrections were made during the analysis. 1 ml of methylene chloride was then transferred to a 2 ml autosampler vial and crimp sealed with a Teflon cap. Samples were analyzed with an HP 5890 capillary gas chromatogram, a HP 7673A autosampler and a flame ionization detector. Three ml of methylene chloride was injected in splitless mode (purge on 0.5 min, purge off 10.0 min) onto a 0.25 mm x 30 m length of DB5 capillary column with a stationary phase film thickness of 0.25µm. Helium column flow rate was 2 ml/min and make-up gas flow rate was 30ml/min. Injection temperature was 275ºC and detector temperature was 325ºC. Initial column temperature was 35ºC and held for 0.5 min, then ramped at 15ºC to a final temperature of 300ºC and held for 2 min. Data integration was completed with a HP 3393A integrator.

Calibrations were made in internal standard mode and standards were run in triplicate at seven different concentrations, covering the expected sample range. Calibration standards were prepared by spiking small quantities of methanolic certified standard into autosampler vials containing 1 ml of methylene chloride (with MFT). Standards were analyzed by gas chromatography in the same way as the samples. A multiple point linear regression was performed to determine the linearity and slope of the calibration curve for each analyte. To determine method extraction efficiency, non-petroleum hydrocarbon impacted sand was used to prepare matrix spikes in the same way samples were prepared with an exposure time of approximately 3.5 weeks. Average percent recovery of 4 replicates for the mid range standard was 106.9% for benzene, 98.3% for toluene, 98.1% for ethylbenzene, 97.9% for p+m-xylene, 99.9% for o-xylene, 99.5% for 1,3,5-trimethylbenzene, 99.7% for 1,2,4-trimethylbenzene, 99.9% for 1,2,3-trimethylbenezene, and 96.8% for naphthalene. The extraction efficiency was effective at measuring the total soil extract concentrations of the select gasoline constituents.

Detection limits for these compounds were 0.032, 0.028, 0.036, 0.058, 0.030, 0.033, 0.034, 0.034 and 0.055 mg/kg wet soil for benzene, toluene, ethylbenzene, P,M-xylene, O-xylene, 1,3,5-trimethylbenzene, 1,2,4-trimethylbenzene, 1,2,3-trimethylbenzene and naphthalene for the November 2007 analysis and 0.029, 0.029, 0.014, 0.014, 0.021, 0.020, 0.033, 0.015 and 0.033 mg/kg wet soil respectively for the July 2009 analysis.
The soil extraction concentrations are shown in Appendix A. 157 soil samples from collected from the 10 boreholes located in the source zone contained very high extraction analysis concentrations which exceeded the concentration rage of standards. These samples were then diluted for 5-100 times.

Table B.1 Determination of mole fraction of gasoline constituents of interest measured from site specific NAPL.
ORGANIC GEOCHEMISTRY LABORATORY
Client: Dale Holtze -Gasoline Samples
Laboratory Number: 080302
BTEX, Trimethylbenzenes and Naphthalene Analysis
Samples submitted: Apr 01, 2008

Analyst: Marianne VanderGriendt
Report Date: Apr 7, 2008

Sample Identification	Date Collected	Dilution (in Mecl2) (data is dilution corrected)	MDL (Mar 24, 2008) <u>*μg/ml Mecl2*</u> <u>1:1000 dilution</u> <u>1:5000 dilution</u>					
<u>*Units are mg/Kg Gasoline*</u>								
LNAPL-A	14-Feb-08	1:5000 dilution (4ul/20ml mecl2)	Constituent$_i$	Molar Mass (g/mol)	C_i mg/kg gas	M_i (g)	n_i	$X_{i\text{-NAPL}}$
			Benzene	78.1	19504	20	0.25	0.027
			Toluene	92.1	7221	7	0.08	0.008
			Ethylbenzene	106.2	17942	18	0.17	0.018
			P,M-xylene	106.2	54931	55	0.52	0.056
			O-xylene	106.2	21328	21	0.20	0.022
			1,3,5-TMB	120.2	16702	17	0.14	0.015
			1,2,4-TMB	120.2	52937	53	0.44	0.048
			1,2,3-TMB	120.2	13053	13	0.11	0.012
			Naphthalene	128.2	5005	5	0.04	0.004
						Total n in 1 mL NAPL	1.94	

Notes:

mecl2	methylene chloride
C_i	measured concentration of gasoline constituent in NAPL
M_i	estimated mass of gasoline constituent in 1 kg NAPL
n_i	moles of gasoline constituent present in 1 kg NAPL
$X_{i\text{-NAPL}}$	mole fraction of gasoline constituent of interest, where Xi = ni/Total n * 0.21
0.21	BTEXTMB compounds make up approximately 21% of NAPL

Table B.2 Summary of soil coring results for BTEXTMB at borehole BH-301/MW-301

ORGANIC GEOCHEMISTRY LABORATORY

Client: Dale Holtze

Laboratory Number: 071114

BTEX, Trimethylbenzenes and Naphthalene Analysis (Soil Extraction (approx 6 g soil) with Methylene Chloride(5ml)

Samples submitted: Nov 26 and Nov 30, 2007

Analyst: Marianne VanderGriendt

Sample ID	Depth of Top Interval (m bgs)	Depth of Bottom Interval (m bgs)	Length of Core Recovered (m)	Depth in Core Sample Taken (m) from Top	Depth (m bgs)	Sample Elevation (m AMSL)	Depth Error (m)	Benzene mg/kg wet soil	Toluene mg/kg wet soil	Ethylbenzene mg/kg wet soil	P,M-xylene mg/kg wet soil	O-xylene mg/kg wet soil	TMB-1,3,5 mg/kg wet soil	TMB-1,2,4 mg/kg wet soil	TMB-1,2,3 mg/kg wet soil	Naphthalene mg/kg wet soil	BTEXTMB mg/kg (wet soil)
							MDL	0.032	0.028	0.036	0.058	0.030	0.033	0.034	0.034	0.055	Total
BH-301-3	2.29	3.05	-	0.3	2.6	308.81	-	8.08	18.36	28.38	47.87	15.51	35.40	108.91	37.63	18.62	382.15
BH-301-1	2.29	3.05	-	0.5	2.8	308.61	-	8.63	16.85	20.34	31.22	12.17	21.67	67.62	24.87	13.98	260.72
BH-301-4	3.81	4.58	0.53	0.2	4.0	307.39	0.239	5.01	8.28	6.14	5.85	3.27	1.58	5.54	1.72	3.37	49.89
BH-301-5	3.81	4.58	0.53	0.4	4.2	307.19	0.239	17.52	19.76	12.86	15.21	5.75	4.24	13.22	4.59	8.07	122.18
BH-301-6	4.58	5.33	0.69	0.1	4.7	306.72	0.065	21.35	21.42	7.73	39.77	16.68	11.95	37.21	9.40	4.85	226.81
BH-301-7	4.58	5.33	0.69	0.3	4.9	306.52	0.065	29.32	32.95	13.29	66.23	27.94	19.08	61.94	15.88	8.08	368.87
BH-301-8	4.58	5.33	0.69	0.5	5.1	306.32	0.065	89.00	93.41	32.07	157.41	66.93	41.44	145.16	37.14	18.29	905.20
BH-301-9	5.33	6.07	0.72	0.2	5.5	305.87	0.015	25.88	23.59	15.60	72.31	24.06	20.68	71.69	19.78	13.98	383.94
BH-301-10	5.33	6.07	0.72	0.5	5.8	305.57	0.015	24.37	20.76	17.24	78.66	18.26	22.00	76.15	20.71	11.60	386.67
BH-301-11	6.07	6.86	0.62	0.1	6.2	305.23	0.169	15.48	12.62	11.04	47.44	16.44	12.64	45.04	12.23	6.73	243.55
BH-301-11	6.07	6.86	0.62	0.1	6.2	305.23	0.169	15.22	12.75	11.01	47.91	16.84	12.14	42.72	11.66	6.52	241.51
BH-301-12	6.07	6.86	0.62	0.3	6.4	305.03	0.169	77.57	59.60	47.24	213.69	71.27	52.82	203.26	54.51	31.69	1096.60
BH-301-13	6.07	6.86	0.62	0.5	6.6	304.83	0.169	28.37	52.26	25.91	106.10	42.07	23.24	92.74	22.86	11.41	553.14
BH-301-14	6.86	7.62	0.75	0.2	7.1	304.34	0.012	49.31	196.43	66.25	191.12	83.79	32.13	131.29	31.68	16.43	1073.35
BH-301-15	6.86	7.62	0.75	0.4	7.3	304.14	0.012	20.18	69.57	30.57	90.44	38.11	14.83	57.76	13.95	7.36	471.34
BH-301-16	6.86	7.62	0.75	0.6	7.5	303.94	0.012	123.34	445.34	187.61	549.15	231.03	89.01	342.98	83.82	42.80	2875.25
BH-301-16	6.86	7.62	0.75	0.6	7.5	303.94	0.012	117.60	432.78	182.83	531.81	224.27	86.87	333.59	81.34	45.21	2792.38
BH-301-18	7.62	8.38	0.75	0.40	8.0	303.38	0.012	0.15	3.03	0.67	2.37	1.02	0.17	0.69	0.20	0.20	11.89
BH-301-19	7.62	8.38	0.75	0.70	8.3	303.08	0.012	0.26	2.98	0.77	2.79	1.19	0.28	1.11	0.32	0.32	14.00
BH-301-20	8.38	9.14	0.75	0.20	8.6	302.82	0.012	2.34	9.29	4.07	12.52	5.27	1.85	7.49	1.87	1.12	63.60
BH-301-21	8.38	9.14	0.75	0.40	8.8	302.62	0.012	0.28	1.99	1.00	3.68	1.52	0.34	1.33	0.20	0.40	15.94
BH-301-22	8.38	9.14	0.75	0.60	9.0	302.42	0.012	0.25	1.19	1.09	4.06	1.67	0.32	1.28	0.37	0.38	16.36
BH-301-23	9.14	9.91	0.75	0.20	9.3	302.06	0.012	4.25	13.30	7.24	22.05	9.49	3.77	15.06	3.80	2.50	113.01
BH-301-23	9.14	9.91	0.75	0.20	9.3	302.06	0.012	4.19	13.50	7.12	21.91	9.43	3.90	14.91	3.67	2.04	112.02
BH-301-24	9.14	9.91	0.75	0.40	9.5	301.86	0.012	8.95	25.74	13.27	40.03	16.82	6.32	25.06	6.19	3.38	202.63
BH-301-24	9.14	9.91	0.75	0.40	9.5	301.86	0.012	8.67	26.17	13.43	40.20	16.98	6.35	24.73	6.03	3.23	202.98
BH-301-25	9.14	9.91	0.75	0.60	9.7	301.66	0.012	5.07	15.20	8.10	24.47	10.40	4.03	15.95	3.95	2.26	124.29
BH-301-25	9.14	9.91	0.75	0.60	9.7	301.66	0.012	4.91	15.41	7.85	24.14	10.36	3.99	15.67	3.81	2.17	122.81
BH-301-26	9.91	10.67	0.75	0.20	10.1	301.29	0.012	3.77	10.19	5.29	16.13	6.72	2.43	9.55	2.38	1.38	80.69
BH-301-26	9.91	10.67	0.75	0.20	10.1	301.29	0.012	3.77	10.34	5.00	15.66	6.61	2.43	9.37	2.31	1.24	78.98
BH-301-27	9.91	10.67	0.75	0.40	10.3	301.09	0.012	3.00	8.56	4.27	13.07	5.47	1.97	7.75	1.93	1.17	65.74
BH-301-27	9.91	10.67	0.75	0.40	10.3	301.09	0.012	2.92	8.68	4.07	12.73	5.37	2.02	7.58	1.86	1.02	64.34
BH-301-28	9.91	10.67	0.75	0.60	10.5	300.89	0.012	3.08	8.24	4.45	13.66	5.69	2.05	8.11	2.02	1.20	67.86
BH-301-28	9.91	10.67	0.75	0.60	10.5	300.89	0.012	3.29	8.33	4.37	13.55	5.63	2.11	7.98	1.96	1.03	67.40
BH-301-29	10.67	11.43	0.75	0.30	11.0	300.43	0.012	1.17	3.28	1.96	6.23	2.60	0.91	3.60	0.93	0.67	30.18
BH-301-29	10.67	11.43	0.75	0.30	11.0	300.43	0.012	1.20	3.31	1.85	6.01	2.54	0.95	3.52	0.96	0.53	29.43
BH-301-30	10.67	11.43	0.75	0.60	11.3	300.13	0.012	2.62	6.99	3.77	11.57	4.83	1.73	6.81	1.71	1.02	57.44

Table B.2 Summary of soil coring results for BTEXTMB at borehole BH-301/MW-301
ORGANIC GEOCHEMISTRY LABORATORY
Client: Dale Holtze
Laboratory Number: 071114
BTEX, Trimethylbenzenes and Naphthalene Analysis (Soil Extraction (approx 6 g soil) with Methylene Chloride(5ml)
Samples submitted: Nov 26 and Nov 30, 2007

Analyst: Marianne VanderGriendt

Sample ID	Depth of Top lnterval (m bgs)	Depth of Bottom Interval (m bgs)	Length of Core Recovered (m)	Depth in Core Sample Taken (m) from Top	Depth (m bgs)	Sample Elevation (m AMSL)	Depth Error (m)	Benzene mg/kg wet soil	Toluene mg/kg wet soil	Ethylbenzene mg/kg wet soil	P,M-xylene mg/kg wet soil	O-xylene mg/kg wet soil	TMB-1,3,5 mg/kg wet soil	TMB-1,2,4 mg/kg wet soil	TMB-1,2,3 mg/kg wet soil	Naphthalene mg/kg wet soil	BTEXTMB mg/kg (wet soil)
							MDL	0.032	0.028	0.036	0.058	0.030	0.033	0.034	0.034	0.055	Total
BH-301-30	10.67	11.43	0.75	0.60	11.3	300.13	0.012	2.14	7.08	2.63	11.56	4.84	1.79	6.78	1.67	0.91	55.79
BH-301-31	11.43	12.19	0.75	0.10	11.5	299.87	0.012	0.49	1.27	0.83	2.84	1.21	0.30	1.24	0.34	0.30	12.89
BH-301-32	11.43	12.19	0.75	0.50	11.9	299.47	0.012	0.37	0.60	0.50	1.80	0.68	0.18	0.74	0.22	0.24	7.79
BH-301-33	11.43	12.19	0.75	0.70	12.1	299.27	0.012	0.39	0.15	0.33	1.24	0.31	0.12	0.49	0.15	0.14	4.89

Table B.3 Summary of soil coring results for BTEXTMB at borehole BH-302/MW-302

ORGANIC GEOCHEMISTRY LABORATORY

Client: Dale Holtze

Laboratory Number: 071114

BTEX, Trimethylbenzenes and Naphthalene Analysis (Soil Extraction (approx 6 g soil) with Methylene Chloride(5ml)

Samples submitted: Nov 26 and Nov 30, 2007

Analyst: Marianne VanderGriendt

Sample ID	Depth of Top lnterval (m bgs)	Depth of Bottom Interval (m bgs)	Length of Core Recovered (m)	Depth in Core Sample Taken (m) from Top	Depth (m bgs)	Sample Elevation (m AMSL)	Depth Error (m)	Benzene mg/kg wet soil	Toluene mg/kg wet soil	Ethylbenzene mg/kg wet soil	P,M-xylene mg/kg wet soil	O-xylene mg/kg wet soil	TMB-1,3,5 mg/kg wet soil	TMB-1,2,4 mg/kg wet soil	TMB-1,2,3 mg/kg wet soil	Naphthalene mg/kg wet soil	BTEXTMB mg/kg (wet soil)
							MDL	0.032	0.028	0.036	0.058	0.030	0.033	0.034	0.034	0.055	Total
BH-302-1	0	1.524	0.57	0.5	0.5	310.63	0.954	5.77	7.16	8.78	50.19	5.91	14.53	50.72	14.84	11.04	168.93
BH-302-2	1.524	2.286	0.54	0.2	1.724	309.41	0.222	1.57	0.87	0.46	0.47	0.25	0.90	2.82	1.44	2.37	11.15
BH-302-3	1.524	2.286	0.54	0.4	1.924	309.21	0.222	3.67	1.55	2.21	7.48	1.00	6.73	23.71	10.22	14.55	71.12
BH-302-4	3.049	3.81	0.32	0.2	3.249	307.88	0.441	13.38	9.46	10.85	59.64	3.70	16.76	56.39	16.34	10.07	196.59
BH-302-5	3.81	4.579	0.41	0.13	3.94	307.19	0.359	57.36	50.15	25.61	158.64	52.60	46.43	162.22	44.03	23.14	620.19
BH-302-6	3.81	4.579	0.41	0.33	4.14	306.99	0.359	27.88	32.73	23.19	132.48	50.44	35.83	126.12	34.51	17.02	480.20
BH-302-7	4.579	5.334	0.41	0.13	4.709	306.42	0.345	67.38	63.37	76.59	231.60	80.20	47.40	164.19	43.87	23.49	798.08
BH-302-8	4.579	5.334	0.41	0.33	4.909	306.22	0.345	17.45	30.70	41.25	118.57	49.25	23.94	89.76	23.34	16.11	410.36
BH-302-9	5.334	6.069	0.65	0.2	5.534	305.60	0.085	21.47	39.68	37.48	102.59	42.16	21.24	78.52	19.76	10.70	373.60
BH-302-10	5.334	6.069	0.65	0.4	5.734	305.40	0.085	92.86	145.89	69.93	286.65	117.17	63.40	234.89	57.16	26.36	1094.30
BH-302-11	6.069	6.858	0.75	0.2	6.269	304.86	0.039	58.66	113.15	72.73	215.13	87.11	43.45	497.47	41.68	19.28	1148.65
BH-302-12	6.069	6.858	0.75	0.4	6.469	304.66	0.039	86.01	157.59	67.14	279.36	113.39	53.91	201.61	49.72	23.13	1031.87
BH-302-13	6.069	6.858	0.75	0.6	6.669	304.46	0.039	159.31	285.13	169.20	495.46	200.33	96.51	356.80	88.16	43.10	1894.00
BH-302-14	6.858	7.62	0.75	0.1	6.958	304.17	0.012	132.11	256.69	147.05	424.34	175.80	80.89	316.85	78.86	42.03	1654.62
BH-302-15	6.858	7.62	0.75	0.3	7.158	303.97	0.012	58.71	104.66	61.30	178.84	73.93	32.53	129.73	31.47	17.23	688.39
BH-302-16	6.858	7.62	0.75	0.5	7.358	303.77	0.012	0.36	2.57	0.54	2.04	0.82	0.22	0.87	0.26	0.29	7.96
BH-302-17	6.858	7.62	0.75	0.7	7.558	303.57	0.012	0.33	2.39	0.50	1.93	0.77	0.21	0.85	0.25	0.23	7.47
BH-302-18	7.62	8.382	0.34	0.17	7.79	303.34	0.422	0.80	2.95	0.69	2.50	1.00	0.29	1.15	0.33	0.26	9.97
BH-302-19	8.382	9.144	0.75	0.2	8.58	302.55	0.012	0.42	1.82	0.99	3.45	1.42	0.36	1.43	0.40	0.37	10.67
BH-302-20	8.382	9.144	0.75	0.7	9.08	302.05	0.012	0.43	0.88	0.63	2.27	0.88	0.22	0.88	0.26	0.27	6.71
BH-302-21	9.144	9.906	0.75	0.2	9.34	301.79	0.012	0.56	1.79	1.10	3.84	1.54	0.43	1.71	0.48	0.54	11.99
BH-302-22	9.144	9.906	0.75	0.4	9.54	301.59	0.012	0.48	1.28	0.64	2.33	0.99	0.30	1.23	0.33	0.31	7.89
BH-302-23	9.144	9.906	0.75	0.6	9.74	301.39	0.012	0.54	1.62	0.64	2.34	0.99	0.28	1.19	0.33	0.30	8.24
BH-302-24	9.906	10.668	0.75	0.2	10.11	301.02	0.012	0.57	0.84	0.48	1.86	0.72	0.37	1.49	0.40	0.28	7.01
BH-302-25	9.906	10.668	0.75	0.6	10.51	300.62	0.012	0.17	0.11	0.29	1.30	0.44	0.32	1.24	0.34	0.26	4.47
BH-302-26	10.668	11.43	0.75	0.65	11.32	299.81	0.012	0.83	1.56	0.94	3.12	1.23	0.54	2.09	0.58	0.33	11.24
BH-302-27	11.43	12.192	0.75	0.2	11.63	299.50	0.012	0.61	0.62	0.60	2.44	0.85	0.44	1.72	0.47	0.31	8.07
BH-302-28	11.43	12.192	0.75	0.4	11.83	299.30	0.012	0.57	0.54	0.54	2.13	0.79	0.34	1.37	0.38	0.26	6.91
BH-302-29	11.43	12.192	0.75	0.6	12.03	299.10	0.012	0.62	0.61	0.54	2.19	0.79	0.29	1.16	0.34	0.28	6.81
BH-302-30	12.192	12.954	0.75	0.2	12.39	298.74	0.012	0.56	0.74	0.58	2.33	0.79	0.34	1.36	0.39	0.33	7.41
BH-302-31	12.192	12.954	0.75	0.4	12.59	298.54	0.012	0.46	0.59	0.45	1.76	0.61	0.23	0.98	0.28	0.22	5.56
BH-302-32	12.192	12.954	0.75	0.6	12.79	298.34	0.012	0.52	0.76	0.61	2.35	0.81	0.31	1.34	0.37	0.33	7.41

Table B.3 Summary of soil coring results for BTEXTMB at borehole BH-302/MW-302
ORGANIC GEOCHEMISTRY LABORATORY
Client: Dale Holtze
Laboratory Number: 071114
BTEX, Trimethylbenzenes and Naphthalene Analysis (Soil Extraction (approx 6 g soil) with Methylene Chloride(5ml)
Samples submitted: Nov 26 and Nov 30, 2007

Analyst: Marianne VanderGriendt

Sample ID	Depth of Top lnterval (m bgs)	Depth of Bottom Interval (m bgs)	Length of Core Recovered (m)	Depth in Core Sample Taken (m) from Top	Depth (m bgs)	Sample Elevation (m AMSL)	Depth Error (m)	Benzene mg/kg wet soil	Toluene mg/kg wet soil	Ethylbenzene mg/kg wet soil	P,M-xylene mg/kg wet soil	O-xylene mg/kg wet soil	TMB-1,3,5 mg/kg wet soil	TMB-1,2,4 mg/kg wet soil	TMB-1,2,3 mg/kg wet soil	Naphthalene mg/kg wet soil	BTEXTMB mg/kg (wet soil)
							MDL	0.032	0.028	0.036	0.058	0.030	0.033	0.034	0.034	0.055	Total

Table B.4 Summary of soil coring results for BTEXTMB at borehole BH-303/MW-303

ORGANIC GEOCHEMISTRY LABORATORY

Client: Dale Holtze

Laboratory Number: 071114

BTEX, Trimethylbenzenes and Naphthalene Analysis (Soil Extraction (approx 6 g soil) with Methylene Chloride(5ml)

Samples submitted: Nov 26 and Nov 30, 2007

Analyst: Marianne VanderGriendt

Sample ID	Depth of Top lnterval (m bgs)	Depth of Bottom Interval (m bgs)	Length of Core Recovered (m)	Depth in Core Sample Taken (m) from Top	Depth (m bgs)	Sample Elevation (m AMSL)	Depth Error (m)	Benzene mg/kg wet soil	Toluene mg/kg wet soil	Ethylbenzene mg/kg wet soil	P,M-xylene mg/kg wet soil	O-xylene mg/kg wet soil	TMB-1,3,5 mg/kg wet soil	TMB-1,2,4 mg/kg wet soil	TMB-1,2,3 mg/kg wet soil	Naphthalene mg/kg wet soil	BTEXTMB mg/kg (wet soil)
							MDL	0.032	0.028	0.036	0.058	0.030	0.033	0.034	0.034	0.055	Total
BH-303-1	1.524	3.048	0.25	0.15	1.674	309.44	1.274	5.77	13.35	19.03	8.65	60.27	23.84	82.61	23.59	12.14	247.71
BH-303-1-DUP	1.524	3.048	0.25	0.15	1.674	309.44	1.274	1.57	19.77	20.60	8.77	62.67	25.64	89.03	25.36	13.21	269.63
BH-303-2	3.81	4.472	0.2	0.1	3.91	307.20	0.462	3.67	20.10	15.76	16.73	86.61	25.45	87.18	26.38	16.96	312.43
BH-303-3	4.572	5.334	0.05	0.025	4.597	306.51	0.712	13.38	52.82	37.65	27.50	146.31	40.11	143.63	39.17	20.32	552.35
BH-303-4	5.334	6.069	0.6	0.2	5.534	305.58	0.135	57.36	6.16	10.70	7.16	35.42	11.31	40.07	10.23	5.80	142.59
BH-303-5	5.334	6.069	0.6	0.4	5.734	305.38	0.135	27.88	18.58	32.24	19.78	94.53	27.34	96.10	24.12	12.61	366.72
BH-303-6	6.069	6.858	0.75	0.3	6.369	304.74	0.039	67.38	53.93	89.85	76.39	225.60	54.32	206.97	51.68	22.94	870.58
BH-303-7	6.069	6.858	0.75	0.5	6.569	304.54	0.039	17.45	79.46	143.14	99.09	295.36	64.28	242.50	64.60	28.99	1134.11
BH-303-8	6.069	6.858	0.75	0.7	6.769	304.34	0.039	21.47	98.42	157.60	111.06	331.98	67.24	254.07	66.85	29.91	1248.61
BH-303-9	6.858	7.62	0.75	0.2	7.058	304.05	0.012	130.82	229.27	175.89	527.71	212.29	107.62	400.64	100.04	46.80	2671.07
BH-303-10	6.858	7.62	0.75	0.4	7.258	303.85	0.012	69.90	105.49	52.09	222.72	89.50	42.71	160.01	39.42	18.14	1112.22
BH-303-11	6.858	7.62	0.75	0.6	7.458	303.65	0.012	2.11	2.75	0.72	2.84	1.11	0.29	1.21	0.35	0.32	15.66
BH-303-12	7.62	8.382	0.6	0.1	7.72	303.39	0.162	2.39	3.36	1.91	6.61	2.53	1.04	3.93	1.07	0.69	32.69
BH-303-13	7.62	8.382	0.6	0.3	7.92	303.19	0.162	0.84	1.32	0.75	3.01	1.17	0.38	1.59	0.45	0.36	14.04
BH-303-14	7.62	8.382	0.6	0.5	8.12	302.99	0.162	0.43	0.63	0.85	3.92	1.34	0.50	2.09	0.63	0.52	16.17
BH-303-15	8.382	9.144	0.75	0.2	8.582	302.53	0.012	0.72	0.94	0.97	3.94	1.45	0.53	2.14	0.63	0.57	17.29
BH-303-16	8.382	9.144	0.75	0.4	8.782	302.33	0.012	0.75	0.76	0.96	3.78	1.39	0.50	2.00	0.58	0.50	16.40
BH-303-17	8.382	9.144	0.75	0.6	8.98	302.13	0.012	0.88	0.84	0.90	3.66	1.37	0.42	1.74	0.51	0.44	15.79
BH-303-18	9.144	9.906	0.35	0.2	9.34	301.77	0.41	0.42	0.51	0.71	2.72	0.82	0.52	2.00	0.56	0.46	12.26

Table B.5 Summary of soil coring results for BTEXTMB at borehole BH-304/MW-304

ORGANIC GEOCHEMISTRY LABORATORY

Client: Dale Holtze

Laboratory Number: 071114

BTEX, Trimethylbenzenes and Naphthalene Analysis (Soil Extraction (approx 6 g soil) with Methylene Chloride(5ml)

Samples submitted: Nov 26 and Nov 30, 2007

Analyst: Marianne VanderGriendt

Sample ID	Depth of Top lnterval (m bgs)	Depth of Bottom Interval (m bgs)	Length of Core Recovered (m)	Depth in Core Sample Taken (m) from Top	Depth (m bgs)	Sample Elevation (m AMSL)	Depth Error (m)	Benzene mg/kg (wet soil)	Toluene mg/kg (wet soil)	Ethylbenzene mg/kg (wet soil)	P,M-xylene mg/kg (wet soil)	O-xylene mg/kg (wet soil)	TMB-1,3,5 mg/kg (wet soil)	TMB-1,2,4 mg/kg (wet soil)	TMB-1,2,3 mg/kg (wet soil)	Naphthalene mg/kg wet soil	BTEXTMB mg/kg (wet soil)
							MDL	0.032	0.028	0.036	0.058	0.030	0.033	0.034	0.034	0.055	Total
BH-304-1	1.524	3.048	0.75	0.20	3.25	307.69	0.774	0.45	4.93	14.01	29.08	12.12	16.34	54.84	13.61	6.35	151.73
BH-304-2	1.524	3.048	0.75	0.40	3.45	307.49	0.774	2.57	16.54	27.30	59.86	28.62	51.13	171.97	45.33	22.90	426.23
BH-304-3	1.524	3.048	0.75	0.60	3.65	307.29	0.774	6.37	17.07	7.14	52.44	23.72	22.10	76.02	19.50	10.09	234.45
BH-304-4	3.048	3.810	0.52	0.40	4.21	306.73	0.242	17.98	36.90	20.47	115.34	49.39	36.08	128.15	32.45	16.12	452.88
BH-304-5	3.810	4.572	0.75	0.25	4.82	306.12	0.012	54.26	107.67	56.77	295.28	121.13	85.01	299.37	74.36	32.37	1126.21
BH-304-6	3.810	4.572	0.75	0.45	5.02	305.92	0.012	32.42	66.16	65.37	183.83	76.62	53.60	192.44	48.40	22.64	741.49
BH-304-7	3.810	4.572	0.75	0.65	5.22	305.72	0.012	29.16	63.56	55.81	167.34	68.99	41.49	152.89	43.36	18.95	641.54
BH-304-8	4.572	5.334	0.75	0.20	5.53	305.41	0.012	38.52	93.84	69.21	204.71	84.51	47.20	173.66	44.06	21.41	777.12
BH-304-9	4.572	5.334	0.75	0.40	5.73	305.21	0.012	36.67	95.51	66.19	194.21	81.24	44.95	165.83	42.05	20.84	747.49
BH-304-10	4.572	5.334	0.75	0.60	5.93	305.01	0.012	9.81	31.99	15.12	68.95	29.35	16.99	62.34	15.49	8.15	258.18
BH-304-11	5.334	6.069	0.75	0.25	6.32	304.62	0.012	4.11	15.37	7.55	35.06	15.51	9.76	36.54	9.33	5.14	138.37
BH-304-12	5.334	6.069	0.75	0.50	6.57	304.37	0.012	84.62	210.96	65.42	295.36	117.99	63.60	241.19	59.42	25.90	1164.47
BH-304-12-DUP	5.334	6.069	0.75	0.50	6.57	304.37	0.012	87.22	214.60	105.79	319.68	124.50	67.35	255.72	63.50	28.30	1266.66
BH-304-13	5.334	6.069	0.75	0.70	6.77	304.17	0.012	23.32	50.24	29.62	92.87	36.26	20.18	80.09	19.85	9.02	361.46
BH-304-14	6.069	6.858	0.75	0.20	7.06	303.88	0.039	65.84	90.23	70.98	220.03	86.89	41.86	168.79	41.77	18.10	804.48
BH-304-16	6.858	7.620	0.54	0.35	7.97	302.97	0.222	0.30	0.26	0.40	1.59	0.63	0.27	1.09	0.31	0.25	5.09
BH-304-17	7.620	8.382	0.75	0.30	8.68	302.26	0.012	0.46	0.39	0.61	2.33	0.99	0.42	1.74	0.46	0.32	7.72
BH-304-18	7.620	8.382	0.75	0.50	8.88	302.06	0.012	0.20	0.14	0.35	1.53	0.53	0.32	1.25	0.35	0.28	4.94
BH-304-19	8.382	9.144	0.61	0.25	9.39	301.55	0.15	0.16	0.09	0.37	1.71	0.54	0.36	1.39	0.39	0.27	5.28
BH-304-20	9.144	9.906	0.75	0.20	10.11	300.83	0.012	0.29	0.18	0.47	2.04	0.67	0.42	1.64	0.46	0.36	6.52
BH-304-21	9.144	9.906	0.75	0.20	10.11	300.83	0.012	0.54	0.50	1.18	4.73	1.68	0.73	3.00	0.86	0.50	13.72
BH-304-21-DUP	9.144	9.906	0.75	0.20	10.11	300.83	0.012	0.30	0.17	0.58	2.50	0.83	0.47	1.87	0.52	0.39	7.63
BH-304-22	10.668	11.430	0.75	0.30	11.73	299.21	0.012	0.51	0.51	0.52	2.19	0.76	0.37	1.46	0.41	0.31	7.04
BH-304-23	10.668	11.430	0.75	0.50	11.93	299.01	0.012	0.45	0.25	0.45	1.87	0.67	0.33	1.32	0.37	0.28	5.98
BH-304-24	10.668	11.430	0.75	0.70	12.13	298.81	0.012	0.33	0.15	0.39	1.72	0.58	0.32	1.25	0.35	0.24	5.33
BH-304-25	11.430	12.192	0.75	0.20	12.39	298.55	0.012	0.35	0.19	0.43	1.90	0.64	0.37	1.45	0.41	0.32	6.05
BH-304-26	11.430	12.192	0.75	0.40	12.59	298.35	0.012	0.32	0.19	0.41	1.73	0.63	0.34	1.38	0.38	0.26	5.63
BH-304-27	11.430	12.192	0.75	0.60	12.79	298.15	0.012	0.22	0.09	0.36	1.65	0.53	0.27	1.06	0.31	0.20	4.68

Table B.6 Summary of soil coring results for BTEXTMB at borehole BH-401/MW-401

Client: Dale Holtze (Soil Coring July 13, 14, 2009)

Laboratory Number: 090706

BTEX, Trimethylbenzenes and Naphthalene Analysis (Soil Extraction (approx 5 g soil) in Methylene Chloride(5ml))

Samples submitted: July 13, 14, 2009

Analysis occurred: Samples extracted in the field

Report Date: Nov 10, 2009

LEGEND

0.0 = NOT DETECTED = < MDL

MDL= METHOD DETECTION LIMIT

Mecl2 = methylene chloride

GC Repeat= repeat injection on the Gas Chromatograph

All results are dilution corrected

Sample ID	Depth of Top Interval (m bgs)	Depth of Bottom Interval (m bgs)	Length of Core Recovered (m)	Depth in Core Sample Taken (m) from Top	Depth (m bgs)	Sample Elevation (m AMSL)	Depth Error (m)	Benzene mg/kg (wet soil)	Toluene mg/kg (wet soil)	Ethylbenzene mg/kg (wet soil)	P,M-xylene mg/kg (wet soil)	O-xylene mg/kg (wet soil)	TMB-1,3,5 mg/kg (wet soil)	TMB-1,2,4 mg/kg (wet soil)	TMB-1,2,3 mg/kg (wet soil)	Naphthalene mg/kg wet soil	BTEXTMB mg/kg (wet soil)
							MDL	0.032	0.028	0.0	0.058	0.030	0.033	0.034	0.034	0.055	Total
BH-401-1	2.286	3.048	0.5	0.19	2.5	308.56	0.382	13.3	20.4	30.0	109.0	7.5	29.1	121.8	29.9	8.1	369.05
BH-401-2	3.048	3.810	0.5	0.15	3.2	307.84	0.462	9.3	15.0	14.6	24.6	8.8	10.2	44.6	8.9	1.7	137.79
BH-401-3	3.810	4.579	0.53	0.17	4.0	307.07	0.249	8.8	12.9	10.7	15.3	9.0	11.2	44.7	8.6	1.3	122.48
BH-401-4	3.810	4.579	0.53	0.35	4.2	306.88	0.249	25.1	32.5	39.9	116.6	41.8	29.8	123.3	26.9	8.8	444.82
BH-401-5	3.810	4.579	0.69	0.35	4.2	306.88	0.249	23.9	32.4	38.2	113.9	42.7	29.7	125.4	28.1	8.9	443.10
BH-401-6	3.810	4.579	0.69	0.50	4.3	306.73	0.249	18.3	26.8	29.0	70.4	29.2	25.4	106.2	22.9	6.2	334.34
BH-401-7	4.579	5.334	0.69	0.10	4.7	306.36	0.425	45.2	51.4	64.5	197.4	69.6	54.8	230.6	51.4	15.9	780.86
BH-401-12	4.579	5.334	0.72	0.25	4.8	306.21	0.425	5.8	6.5	8.9	28.2	10.4	6.8	28.7	6.5	2.3	104.09
BH-401-9	5.334	6.069	0.72	0.30	5.6	305.41	0.085	17.4	44.0	29.9	92.7	38.1	15.5	70.2	15.7	4.9	328.53
BH-401-10	5.334	6.069	0.62	0.45	5.8	305.26	0.085	4.2	12.4	8.3	27.1	11.3	4.7	21.0	4.8	1.7	95.47
BH-401-11	5.334	6.069	0.62	0.54	5.9	305.17	0.085	33.4	84.4	57.0	184.5	75.3	29.1	134.3	30.1	9.4	637.47
BH-401-13	6.069	6.858	0.62	0.25	6.3	304.72	0.039	56.2	163.6	83.2	268.2	111.9	42.7	198.9	43.7	13.6	981.94
BH-401-14	6.069	6.858	0.75	0.40	6.5	304.57	0.039	26.8	81.2	40.2	129.6	53.7	20.3	92.4	20.5	6.4	470.96
BH-401-15	6.069	6.858	0.75	0.55	6.6	304.42	0.039	81.9	266.0	132.1	421.5	177.0	63.4	288.7	63.6	20.2	1514.38
BH-401-16	6.069	6.858	0.75	0.70	6.8	304.27	0.039	0.8	5.0	1.6	5.4	2.3	0.7	3.0	0.7	0.3	19.83
BH-401-17	6.858	7.620	0.75	0.05	6.9	304.13	0.012	34.3	96.2	55.9	180.0	74.6	26.3	120.7	26.5	8.7	623.20
BH-401-18	6.858	7.620	0.75	0.25	7.1	303.93	0.012	99.1	242.6	183.1	583.0	240.9	78.1	355.7	77.5	25.7	1885.61
BH-401-19	6.858	7.620	0.75	0.40	7.3	303.78	0.012	61.1	135.1	103.1	322.6	143.4	44.8	214.8	46.5	14.2	1085.70
BH-401-20	6.858	7.620	0.75	0.55	7.4	303.63	0.01	19.8	31.3	36.4	118.1	48.9	14.9	70.7	15.6	5.0	360.71
BH-401-21	6.858	7.620	0.75	0.70	7.6	303.48	0.012	0.2	1.3	1.1	3.7	1.6	0.3	1.2	0.3	0.3	9.93
BH-401-22	7.620	8.382	0.75	0.05	7.7	303.37	0.012	8.7	22.6	16.4	52.3	21.6	7.1	32.9	7.3	2.4	171.24
BH-401-23	7.620	8.382	0.75	0.25	7.9	303.17	0.012	10.8	24.1	20.0	63.7	26.3	8.4	39.3	8.6	2.7	204.10
BH-401-24	7.620	8.382	0.75	0.40	8.0	303.02	0.012	9.9	23.3	17.7	56.0	23.2	7.6	35.4	7.7	2.6	183.44
BH-401-25	7.620	8.382	0.75	0.55	8.2	302.87	0.012	10.4	23.9	19.7	62.5	26.0	8.4	39.0	8.5	2.7	201.00
BH-401-26	7.620	8.382	0.75	0.70	8.3	302.72	0.012	13.9	31.6	25.5	80.5	33.3	10.8	50.1	10.8	3.5	260.08
BH-401-27	8.382	9.144	0.75	0.05	8.4	302.61	0.012	2.7	7.8	5.4	17.5	7.2	2.3	10.2	2.3	0.9	56.31
BH-401-28	8.382	9.144	0.75	0.25	8.6	302.41	0.012	1.6	5.3	3.5	11.6	4.8	1.4	6.3	1.5	0.6	36.61
BH-401-29	8.382	9.144	0.75	0.40	8.8	302.26	0.012	1.5	4.5	3.4	11.4	4.7	1.4	6.3	1.4	0.6	35.44

Table B.7 Summary of soil coring results for BTEXTMB at borehole BH-402/MW-402

Client: Dale Holtze (Soil Coring July 13, 14, 2009)

Laboratory Number: 090706

BTEX, Trimethylbenzenes and Naphthalene Analysis (Soil Extraction (approx 5 g soil) in Methylene Chloride(5ml))

Samples submitted: July 13, 14, 2009

Analysis occurred: Samples extracted in the field

Report Date: Nov 10, 2009

LEGEND

0.0 = NOT DETECTED = < MDL

MDL= METHOD DETECTION LIMIT

Mecl2 = methylene chloride

GC Repeat= repeat injection on the Gas Chromatograph

All results are dilution corrected

Sample ID	Depth of Top lnterval (m bgs)	Depth of Bottom Interval (m bgs)	Length of Core Recovered (m)	Depth in Core Sample Taken (m) from Top	Depth (m bgs)	Sample Elevation (m AMSL)	Depth Error (m)	Benzene mg/kg (wet soil)	Toluene mg/kg (wet soil)	Ethylbenzene mg/kg (wet soil)	P,M-xylene mg/kg (wet soil)	O-xylene mg/kg (wet soil)	TMB-1,3,5 mg/kg (wet soil)	TMB-1,2,4 mg/kg (wet soil)	TMB-1,2,3 mg/kg (wet soil)	Naphthalene mg/kg wet soil	BTEXTMB mg/kg (wet soil)
							MDL	0.032	0.028	0.036	0.058	0.030	0.033	0.034	0.034	0.055	Total
BH-402-1	2.286	3.048	0.38	0.18	2.5	308.62	0.382	16.2	19.8	29.9	98.3	8.4	25.6	109.8	27.6	8.2	343.82
BH-402-2	3.048	3.81	0.33	0.165	3.2	307.88	0.432	18.0	24.3	32.8	104.5	10.5	29.5	127.0	31.2	9.0	386.66
BH-402-2	3.048	3.81	0.33	0.165	3.2	307.88	0.439	18.0	24.3	31.8	102.8	10.5	28.9	125.4	30.7	8.4	380.79
BH-402-4	3.81	4.579	0.18	0.11	3.9	307.17	0.575	8.8	6.7	13.0	49.0	2.7	7.7	37.5	10.0	3.6	138.94
BH-402-5	4.579	5.334	0.59	0.05	4.6	306.46	0.145	23.4	22.8	24.5	78.0	12.8	22.5	97.1	23.5	5.9	310.47
BH-402-6	5.334	6.069	0.59	0.15	5.5	305.61	0.145	20.6	27.0	30.0	85.0	32.2	17.5	79.7	17.7	5.0	314.62
BH-402-7	5.334	6.069	0.59	0.3	5.6	305.46	0.145	21.6	31.9	27.1	75.3	29.9	17.0	75.3	16.3	4.4	298.83
BH-402-8	5.334	6.069	0.59	0.45	5.8	305.31	0.145	5.4	6.4	8.3	25.6	9.5	5.4	23.7	5.2	1.5	90.92
BH-402-9	5.334	6.069	0.75	0.55	5.9	305.21	0.039	18.3	47.9	28.7	88.8	35.2	18.2	80.5	17.8	4.9	340.32
BH-402-10	6.069	6.858	0.75	0.15	6.2	304.87	0.039	37.9	85.5	51.6	166.0	65.7	33.0	147.8	32.6	9.2	629.30
BH-402-11	6.069	6.858	0.75	0.3	6.4	304.72	0.039	64.5	166.2	94.3	308.9	122.0	58.5	264.3	59.3	17.6	1155.48
BH-402-12	6.069	6.858	0.75	0.45	6.5	304.57	0.039	43.6	61.7	67.4	223.7	87.3	43.6	198.1	44.1	12.8	782.36
BH-402-13	6.069	6.858	0.75	0.6	6.7	304.42	0.039	58.1	52.5	81.7	284.1	96.1	52.2	236.0	52.5	16.5	929.66
BH-402-14	6.069	6.858	0.75	0.69	6.8	304.33	0.012	53.5	51.1	84.4	292.9	94.6	48.9	218.8	48.4	15.7	908.35
BH-402-15	6.858	7.62	0.75	0.15	7.0	304.08	0.012	49.2	117.2	72.1	234.0	95.9	40.8	184.2	41.1	12.2	846.57
BH-402-16	6.858	7.62	0.75	0.3	7.2	303.93	0.012	49.9	115.2	70.8	230.8	93.5	40.2	182.0	40.2	12.1	834.59
BH-402-17	6.858	7.62	0.75	0.45	7.3	303.78	0.012	34.8	69.9	50.3	164.4	65.0	30.1	135.6	30.2	8.9	588.99
BH-402-18	6.858	7.62	0.75	0.6	7.5	303.63	0.012	97.9	231.8	122.1	393.7	163.7	65.3	307.9	66.9	19.2	1468.33
BH-402-19	7.62	8.382	0.75	0.05	7.7	303.42	0.012	13.6	26.1	19.1	59.1	22.3	11.3	50.2	11.1	3.2	215.96
BH-402-20	7.62	8.382	0.75	0.2	7.8	303.27	0.012	4.6	11.5	7.0	23.8	9.5	3.6	17.4	3.9	1.2	82.38
BH-402-21	7.62	8.382	0.75	0.35	8.0	303.12	0.012	4.0	10.8	7.2	24.8	10.0	3.9	18.8	4.2	1.3	85.02
BH-402-22	7.62	8.382	0.75	0.5	8.1	302.97	0.012	11.3	23.5	15.2	51.2	20.0	7.9	37.7	8.4	2.3	177.46
BH-402-23	7.62	8.382	0.75	0.65	8.3	302.82	0.012	33.8	82.1	49.1	157.6	63.1	27.3	124.5	27.7	8.1	573.51
BH-402-24	8.382	9.144	0.55	0.1	8.5	302.61	0.212	5.7	13.1	8.6	29.1	11.5	4.5	21.1	4.7	1.4	99.73
BH-402-25	8.382	9.144	0.55	0.25	8.6	302.46	0.212	3.0	8.2	4.7	16.2	6.4	2.4	11.2	2.5	0.9	55.32
BH-402-26	8.382	9.144	0.55	0.4	8.8	302.31	0.212	2.0	5.8	3.2	11.3	4.5	1.7	8.1	1.9	0.2	38.72
BH-402-27	8.382	9.144	0.55	0.5	8.9	302.21	0.212	1.4	4.4	2.3	8.4	3.4	1.3	6.0	1.4	0.6	29.19
BH-402-30	9.144	9.906	0.55	0.4	9.5	301.55	0.212	3.7	8.4	5.5	19.0	7.6	2.8	13.7	3.1	1.0	64.81

Table B.8 Summary of soil coring results for BTEXTMB at borehole BH-403/MW-403

Client: Dale Holtze (Soil Coring July 13, 14, 2009)

Laboratory Number: 090706

BTEX, Trimethylbenzenes and Naphthalene Analysis (Soil Extraction (approx 5 g soil) in Methylene Chloride(5ml))

Samples submitted: July 13, 14, 2009

Analysis occurred: Samples extracted in the field

Report Date: Nov 10, 2009

LEGEND

0.0 = NOT DETECTED = < MDL

MDL= METHOD DETECTION LIMIT

Mecl2 = methylene chloride

GC Repeat= repeat injection on the Gas Chromatograph

All results are dilution corrected

Sample ID	Depth of Top lnterval (m bgs)	Depth of Bottom Interval (m bgs)	Length of Core Recovered (m)	Depth in Core Sample Taken (m) from Top	Depth (m bgs)	Sample Elevation (m AMSL)	Depth Error (m)	Benzene mg/kg (wet soil)	Toluene mg/kg (wet soil)	Ethylbenzene mg/kg (wet soil)	P,M-xylene mg/kg (wet soil)	O-xylene mg/kg (wet soil)	TMB-1,3,5 mg/kg (wet soil)	TMB-1,2,4 mg/kg (wet soil)	TMB-1,2,3 mg/kg (wet soil)	Naphthalene mg/kg wet soil	BTEXTMB mg/kg (wet soil)
							MDL	0.032	0.028	0.036	0.058	0.030	0.033	0.034	0.034	0.055	Total
BH-403-1	1.524	2.286	0.25	0.5	1.8	309.17	0.262	7.3	7.82	14.1	54.5	5.3	11.8	52.3	12.5	3.8	169.54
BH-403-2	2.286	3.048	0.20	0.48	2.5	308.45	0.282	11.4	10.65	21.3	78.7	7.0	15.5	64.9	15.5	5.0	229.85
BH-403-3	3.05	4.58	0.25	0.53	3.3	307.64	1.001	22.4	29.90	0.0	50.7	20.4	11.7	55.8	7.1	2.2	200.37
BH-403-5	3.81	4.58	0.35	0.65	4.2	306.78	0.119	38.4	52.72	69.6	206.5	82.5	55.9	225.2	48.1	29.8	808.85
BH-403-6	3.81	4.58	0.55	0.65	4.4	306.58	0.119	11.8	29.18	20.9	67.1	28.0	12.6	52.8	11.5	7.7	241.48
BH-403-7	4.58	5.33	0.45	0.75	5.0	305.91	0.005	44.3	60.50	59.5	180.1	69.7	45.1	187.0	40.1	23.6	709.92
BH-403-9	5.334	6.069	0.05	0.75	5.4	305.56	0.005	21.6	29.02	32.3	109.0	44.4	20.3	89.6	20.0	6.6	372.79
BH-403-10	5.334	6.069	0.20	0.75	5.5	305.41	0.015	1.6	2.57	2.9	10.3	4.1	1.8	7.9	1.8	0.7	33.76
BH-403-11	5.334	6.069	0.35	0.75	5.7	305.26	0.015	0.6	0.95	1.1	4.5	1.7	0.7	3.3	0.8	0.6	14.29
BH-403-12	5.334	6.069	0.50	0.75	5.8	305.11	0.015	0.2	0.45	0.6	2.5	0.9	0.4	1.7	0.4	0.3	7.48
BH-403-13	5.334	6.069	0.65	0.75	6.0	304.96	0.015	0.2	0.68	0.7	2.7	1.0	0.3	1.4	0.4	0.3	7.68
BH-403-16	6.069	6.858	0.47	0.75	6.5	304.40	0.015	20.2	24.13	26.6	86.2	37.5	9.4	58.0	12.5	3.7	278.21
BH-403-17	6.069	6.858	0.60	0.75	6.7	304.27	0.039	0.3	0.72	0.5	1.7	0.7	0.2	0.8	0.2	0.1	5.15
BH-403-18	6.069	6.858	0.70	0.75	6.8	304.17	0.039	0.2	0.60	0.5	1.8	0.7	0.2	0.7	0.2	0.1	4.83
BH-403-19	6.858	7.62	0.05	0.75	6.9	304.03	0.039	0.3	1.30	0.5	1.8	0.7	0.2	0.9	0.2	0.2	6.03
BH-403-20	6.858	7.62	0.20	0.75	7.1	303.88	0.012	0.3	1.46	0.6	2.0	0.8	0.2	1.1	0.3	0.2	7.00
BH-403-22	6.858	7.62	0.50	0.75	7.4	303.58	0.012	0.3	1.78	0.4	1.3	0.5	0.2	0.7	0.2	0.2	5.37
BH-403-23	6.858	7.62	0.65	0.75	7.5	303.43	0.01	0.2	1.34	0.3	1.1	0.4	0.1	0.6	0.2	0.2	4.56
BH-403-24	7.62	8.382	0.05	0.75	7.7	303.27	0.012	0.6	2.03	0.8	2.6	1.1	0.4	1.8	0.4	0.2	9.91
BH-403-25	7.62	8.382	0.20	0.75	7.8	303.12	0.012	0.4	1.57	0.5	1.7	0.7	0.2	1.0	0.2	0.1	6.25
BH-403-26	7.62	8.382	0.35	0.75	8.0	302.97	0.012	0.4	1.60	0.6	2.0	0.8	0.3	1.3	0.3	0.2	7.58
BH-403-27	7.62	8.382	0.50	0.75	8.1	302.82	0.012	0.4	1.48	0.5	1.7	0.7	0.2	1.0	0.2	0.1	6.27
BH-403-28	7.62	8.382	0.65	0.75	8.3	302.67	0.012	1.0	1.89	1.2	4.0	1.7	0.7	3.2	0.7	0.1	14.46
BH-403-29	8.382	9.144	0.10	0.75	8.5	302.46	0.012	0.5	2.33	0.7	2.5	1.0	0.3	1.1	0.3	0.3	8.99

Table B.9 Summary of soil coring results for BTEXTMB at borehole BH-405/MW-405

Client: Dale Holtze (Soil Coring July 13, 14, 2009)

Laboratory Number: 090706

BTEX, Trimethylbenzenes and Naphthalene Analysis (Soil Extraction (approx 5 g soil) in Methylene Chloride(5ml))

Samples submitted: July 13, 14, 2009

Analysis occurred: Samples extracted in the field

Report Date: Nov 10, 2009

LEGEND

0.0 = NOT DETECTED = < MDL

MDL= METHOD DETECTION LIMIT

Mecl2 = methylene chloride

GC Repeat= repeat injection on the Gas Chromatograph

All results are dilution corrected

Sample ID	Depth of Top lnterval (m bgs)	Depth of Bottom Interval (m bgs)	Length of Core Recovered (m)	Depth in Core Sample Taken (m) from Top	Depth (m bgs)	Sample Elevation (m AMSL)	Depth Error (m)	Benzene mg/kg (wet soil)	Toluene mg/kg (wet soil)	Ethylbenzene mg/kg (wet soil)	P,M-xylene mg/kg (wet soil)	O-xylene mg/kg (wet soil)	TMB-1,3,5 mg/kg (wet soil)	TMB-1,2,4 mg/kg (wet soil)	TMB-1,2,3 mg/kg (wet soil)	Naphthalene mg/kg wet soil	BTEXTMB mg/kg (wet soil)
							MDL	0.032	0.028	0.036	0.058	0.030	0.033	0.034	0.034	0.055	Total
BH-405-1	4.579	5.334	0.75	0.05	4.63	306.28	0.005	18.8	56.2	38.52	129.2	54.8	23.2	102.4	23.1	7.6	453.91
BH-405-2	4.579	5.334	0.75	0.25	4.83	306.08	0.005	5.9	18.6	11.91	39.4	16.1	6.6	28.4	6.5	2.2	135.54
BH-405-3	4.58	5.33	0.75	0.55	5.13	305.78	0.005	9.9	21.2	19.90	67.1	27.2	10.7	46.5	10.5	3.9	217.02
BH-405-4	4.58	5.33	0.75	0.70	5.28	305.63	0.005	37.0	69.7	69.94	229.9	95.0	37.0	159.3	35.9	12.7	746.41
BH-405-5	5.33	6.07	0.75	0.05	5.38	305.53	0.015	34.8	88.1	61.74	202.4	85.4	33.0	144.4	32.7	10.6	693.06
BH-405-6	5.33	6.07	0.75	0.20	5.53	305.38	0.015	40.0	101.6	75.49	245.4	103.7	40.5	174.7	39.3	12.7	833.32
BH-405-7	5.334	6.069	0.75	0.35	5.68	305.23	0.015	63.6	200.8	106.46	346.0	146.1	57.1	258.2	57.1	17.6	1253.00
BH-405-8	5.334	6.069	0.75	0.50	5.83	305.08	0.015	48.7	167.9	82.51	264.2	111.2	45.5	193.1	43.0	14.3	970.42
BH-405-9	5.334	6.069	0.75	0.65	5.98	304.93	0.015	91.7	323.3	146.30	476.0	203.8	82.3	353.3	78.1	25.8	1780.42
BH-405-11	6.069	6.858	0.62	0.25	6.32	304.59	0.169	8.1	28.6	12.41	42.3	17.9	7.3	33.1	7.3	2.2	159.24
BH-405-11	6.069	6.858	0.62	0.25	6.32	304.59	0.169	8.1	29.0	11.92	41.3	18.0	7.2	32.9	7.1	2.1	157.63
BH-405-12	6.069	6.858	0.62	0.40	6.47	304.44	0.169	21.8	69.4	32.33	111.2	48.6	20.2	95.8	20.5	5.7	425.49
BH-405-13	6.069	6.858	0.62	0.55	6.62	304.29	0.169	13.3	32.2	19.28	65.9	27.1	11.7	55.4	11.9	3.0	239.83
BH-405-14	6.858	7.62	0.75	0.10	6.96	303.95	0.012	1.7	4.9	1.64	5.8	2.4	0.8	3.9	0.9	0.3	22.34
BH-405-15	6.858	7.62	0.75	0.25	7.11	303.80	0.012	2.6	6.7	2.92	9.7	4.2	1.6	8.1	1.7	0.5	37.95
BH-405-16	6.858	7.62	0.75	0.40	7.26	303.65	0.012	0.6	2.9	0.71	2.8	1.1	0.3	1.4	0.4	0.3	10.50
BH-405-17	6.858	7.62	0.75	0.55	7.41	303.50	0.012	0.3	2.0	0.43	1.7	0.7	0.2	0.8	0.2	0.2	6.55
BH-405-18	6.858	7.62	0.75	0.70	7.56	303.35	0.012	0.5	3.1	0.56	2.3	0.9	0.3	1.2	0.3	0.3	9.41
BH-405-19	7.62	8.382	0.75	0.10	7.72	303.19	0.012	3.6	8.9	4.52	15.1	6.4	2.6	12.5	2.7	0.8	57.23
BH-405-20	7.62	8.382	0.75	0.25	7.87	303.04	0.012	8.2	19.6	10.90	35.5	15.1	6.3	30.7	6.6	1.7	134.63
BH-405-21	7.62	8.382	0.75	0.40	8.02	302.89	0.012	0.4	1.6	0.39	1.6	0.6	0.2	0.7	0.2	0.2	5.80
BH-405-22	7.62	8.382	0.75	0.40	8.02	302.89	0.012	0.4	1.8	0.40	1.6	0.6	0.2	0.7	0.2	0.2	5.96
BH-405-23	7.62	8.382	0.75	0.70	8.32	302.59	0.012	0.3	1.0	0.37	1.4	0.6	0.2	0.8	0.2	0.2	5.06

Table B.10 Summary of soil coring results for BTEXTMB at borehole BH-406/MW-406

Client: Dale Holtze (Soil Coring July 13, 14, 2009)

Laboratory Number: 090706

BTEX, Trimethylbenzenes and Naphthalene Analysis (Soil Extraction (approx 5 g soil) in Methylene Chloride(5ml))

Samples submitted: July 13, 14, 2009

Analysis occurred: Samples extracted in the field

Report Date: Nov 10, 2009

LEGEND

0.0 = NOT DETECTED = < MDL

MDL= METHOD DETECTION LIMIT

Mecl2 = methylene chloride

GC Repeat= repeat injection on the Gas Chromatograph

All results are dilution corrected

Sample ID	Depth of Top lnterval (m bgs)	Depth of Bottom Interval (m bgs)	Length of Core Recovered (m)	Depth in Core Sample Taken (m) from Top	Depth (m bgs)	Sample Elevation (m AMSL)	Depth Error (m)	Benzene mg/kg (wet soil)	Toluene mg/kg (wet soil)	Ethylbenzene mg/kg (wet soil)	P,M-xylene mg/kg (wet soil)	O-xylene mg/kg (wet soil)	TMB-1,3,5 mg/kg (wet soil)	TMB-1,2,4 mg/kg (wet soil)	TMB-1,2,3 mg/kg (wet soil)	Naphthalene mg/kg wet soil	BTEXTMB mg/kg (wet soil)
							MDL	0.032	0.028	0.036	0.058	0.030	0.033	0.034	0.034	0.055	Total
BH-406-1	1.524	2.286	0.41	0.2	1.72	309.18	0.352	0.13	0.3	0.4	1.5	0.0	0.8	3.1	0.7	0.6	7.62
BH-406-2	2.286	3.048	0.39	0.2	2.49	308.41	0.372	4.73	14.4	15.2	33.9	10.3	17.1	67.8	12.6	1.5	177.63
BH-406-3	3.05	3.81	0.26	0.13	3.18	307.72	1.271	5.32	17.2	20.6	55.8	20.6	18.8	78.6	16.4	3.2	236.48
BH-406-4	3.81	4.58	0.66	0.2	4.01	306.89	0.109	62.95	163.7	134.9	445.4	179.4	80.6	350.4	78.7	22.6	1518.58
BH-406-5	3.81	4.58	0.66	0.4	4.21	306.69	0.109	16.46	45.1	36.4	119.8	48.9	21.1	93.4	20.8	6.5	408.37
BH-406-6	3.81	4.58	0.66	0.6	4.41	306.49	0.109	19.91	58.9	44.2	145.2	59.5	25.0	111.6	24.8	7.7	496.91
BH-406-7	4.579	5.334	0.67	0.2	4.78	306.12	0.085	22.01	68.6	44.1	147.1	60.8	25.8	114.2	25.6	7.6	515.67
BH-406-8	4.579	5.334	0.67	0.5	5.08	305.82	0.085	12.08	48.8	28.3	95.6	40.2	17.2	76.4	17.1	5.4	341.04
BH-406-10	5.334	6.069	0.48	0.26	5.59	305.31	0.255	55.81	186.0	92.6	304.1	125.8	53.0	237.6	52.3	16.3	1123.74
BH-406-11	5.334	6.069	0.48	0.4	5.73	305.17	0.255	14.36	42.1	20.3	66.8	27.5	11.7	53.9	12.0	3.6	252.08
BH-406-12	6.069	6.858	0.75	0.05	6.12	304.78	0.039	42.16	121.9	62.1	203.5	83.5	35.2	157.7	35.4	10.8	752.21
BH-406-13	6.069	6.858	0.75	0.25	6.32	304.58	0.039	126.72	364.6	195.4	632.6	249.5	108.4	488.4	104.7	44.9	2315.23
BH-406-14	6.069	6.858	0.75	0.55	6.62	304.28	0.039	34.81	60.0	45.1	151.1	60.9	24.7	118.1	25.9	7.2	527.76
BH-406-15	6.069	6.858	0.75	0.58	6.65	304.25	0.039	76.12	102.6	98.2	325.5	131.0	49.7	243.0	53.4	14.3	1093.76
BH-406-16	6.069	6.858	0.75	0.7	6.77	304.13	0.039	64.65	63.4	72.9	233.7	97.7	49.9	250.2	53.3	10.8	896.42
BH-406-18	6.858	7.62	0.56	0.4	7.26	303.64	0.202	32.30	46.0	38.0	123.5	51.7	24.4	120.2	25.9	6.1	468.20
BH-406-19	7.62	8.382	0.75	0.1	7.72	303.18	0.012	1.54	2.5	1.6	5.7	2.3	0.9	4.5	1.0	0.4	20.44
BH-406-20	7.62	8.382	0.75	0.25	7.87	303.03	0.012	1.05	1.8	1.3	4.9	2.0	0.8	3.9	0.9	0.5	17.16
BH-406-21	7.62	8.382	0.75	0.4	8.02	302.88	0.01	1.41	2.0	1.5	5.2	2.2	0.9	4.4	1.0	0.3	18.98
BH-406-22	7.62	8.382	0.75	0.55	8.17	302.73	0.012	1.62	2.0	1.8	6.4	2.6	1.0	4.6	1.1	0.5	21.57
BH-406-23	7.62	8.382	0.75	0.7	8.32	302.58	0.012	0.49	0.4	0.4	1.5	0.7	0.2	0.7	0.2	0.2	4.78

Table B.11 Summary of soil coring results for BTEXTMB at borehole BH-501/MW-501

Client: Dale Holtze (Soil Coring July 13, 14, 2009)

Laboratory Number: 090706

BTEX, Trimethylbenzenes and Naphthalene Analysis (Soil Extraction (approx 5 g soil) in Methylene Chloride(5ml))

Samples submitted: July 13, 14, 2009

Analysis occurred: Samples extracted in the field

Report Date: Nov 10, 2009

LEGEND

0.0 = NOT DETECTED = < MDL

MDL= METHOD DETECTION LIMIT

Mecl2 = methylene chloride

GC Repeat= repeat injection on the Gas Chromatograph

All results are dilution corrected

Sample ID	Depth of Top lnterval (m bgs)	Depth of Bottom Interval (m bgs)	Length of Core Recovered (m)	Depth in Core Sample Taken (m) from Top	Depth (m bgs)	Sample Elevation (m AMSL)	Depth Error (m)	Benzene mg/kg (wet soil)	Toluene mg/kg (wet soil)	Ethylbenzene mg/kg (wet soil)	P,M-xylene mg/kg (wet soil)	O-xylene mg/kg (wet soil)	TMB-1,3,5 mg/kg (wet soil)	TMB-1,2,4 mg/kg (wet soil)	TMB-1,2,3 mg/kg (wet soil)	Naphthalene mg/kg wet soil	BTEXTMB mg/kg (wet soil)
							MDL	0.032	0.028	0.036	0.058	0.030	0.033	0.034	0.034	0.055	Total
BH-501-1	5.334	6.069	0.5	0.2	5.53	305.66	0.24	17.6	17.44	14.5	28.9	12.7	9.1	46.2	9.5	2.1	158.06
BH-501-2	5.334	6.069	0.5	0.35	5.68	305.51	0.24	20.9	18.89	18.3	43.5	16.9	13.1	60.9	12.7	3.3	208.43
BH-501-3	5.33	6.07	0.53	0.5	5.83	305.36	0.21	90.6	104.44	89.7	247.0	95.7	62.0	281.3	61.0	15.4	1047.27
BH-501-4	5.33	6.07	0.53	0.7	6.03	305.16	0.21	73.6	105.89	88.9	267.4	104.3	55.9	250.9	54.9	15.1	1016.71
BH-501-5	6.07	6.86	0.69	0.05	6.12	305.07	0.10	94.7	207.87	147.4	472.9	193.8	76.1	358.2	78.7	23.3	1652.95
BH-501-6	6.07	6.86	0.69	0.2	6.27	304.92	0.10	77.0	199.34	117.4	375.2	157.0	59.4	281.2	61.6	17.6	1345.74
BH-501-7	6.069	6.858	0.69	0.35	6.42	304.77	0.10	31.4	80.06	51.1	163.4	68.6	26.0	124.1	27.0	8.3	579.74
BH-501-8	6.069	6.858	0.72	0.55	6.62	304.57	0.07	22.9	40.61	30.0	89.4	36.9	17.0	81.4	17.5	4.7	340.42
BH-501-9	6.069	6.858	0.72	0.65	6.72	304.47	0.07	49.7	98.08	79.6	255.6	106.8	39.5	188.2	40.7	12.1	870.23
BH-501-10	6.069	6.858	0.62	0.7	6.77	304.42	0.17	37.0	63.58	60.9	198.1	82.8	30.1	144.4	31.5	9.6	657.96
BH-501-11	6.858	7.62	0.62	0.08	6.94	304.25	0.14	80.1	220.05	129.0	409.1	169.9	64.0	295.2	64.7	19.9	1451.91
BH-501-12	6.858	7.62	0.62	0.2	7.06	304.13	0.14	54.8	130.04	88.1	283.7	118.5	43.4	204.2	44.4	13.5	980.65
BH-501-13	6.858	7.62	0.75	0.3	7.16	304.03	0.01	53.9	166.82	86.7	278.7	116.5	43.9	204.0	44.8	13.3	1008.59
BH-501-15	6.858	7.62	0.75	0.4	7.26	303.93	0.01	69.8	228.12	113.0	358.9	149.9	57.0	261.7	57.3	18.0	1313.75
BH-501-16	6.858	7.62	0.75	0.5	7.36	303.83	0.01	6.2	19.06	11.0	35.6	14.7	5.6	25.8	5.8	1.8	125.50
BH-501-17	6.858	7.62	0.75	0.6	7.46	303.73	0.01	81.8	226.96	130.9	418.9	169.9	66.5	305.4	67.5	20.7	1488.63
BH-501-18	6.858	7.62	0.75	0.7	7.56	303.63	0.01	0.3	3.27	0.8	2.8	1.2	0.3	1.2	0.3	0.3	10.31
BH-501-19	7.62	8.382	0.75	0.05	7.67	303.52	0.01	29.6	81.13	46.6	149.7	62.9	23.2	109.1	23.9	7.2	533.26
BH-501-20	7.62	8.382	0.75	0.1	7.72	303.47	0.01	42.1	115.87	66.2	211.6	88.5	32.8	153.7	33.7	10.4	754.86
BH-501-21	7.62	8.382	0.75	0.2	7.82	303.37	0.01	60.5	154.23	94.4	300.3	124.8	47.5	221.6	48.6	14.6	1066.54
BH-501-22	7.62	8.382	0.75	0.3	7.92	303.27	0.01	64.0	157.97	101.1	321.5	133.4	50.8	237.1	52.3	15.0	1133.29
BH-501-23	7.62	8.382	0.75	0.40	8.0	303.17	0.01	13.7	40.31	23.4	74.6	30.5	11.7	53.3	12.1	3.7	263.31
BH-501-24	7.62	8.382	0.75	0.50	8.12	303.07	0.01	0.4	3.23	0.6	2.2	0.9	0.2	0.9	0.3	0.2	8.96
BH-501-25	7.62	8.382	0.75	0.60	8.2	302.97	0.01	0.2	2.36	0.6	2.3	0.9	0.2	1.0	0.3	0.3	8.18
BH-501-26	7.62	8.382	0.75	0.70	8.3	302.87	0.01	0.1	1.01	0.6	2.2	0.9	0.2	1.0	0.3	0.3	6.53

Table B.11 Summary of soil coring comparision of the results of duplicate samples for QA/QC.

		Benzene	Toluene	Ethylbenzene	P,M-xylene	O-xylene	TMB-1,3,5	TMB-1,2,4	TMB-1,2,3	Naphthalene
Sample ID		0.032	0.028	0.036	0.058	0.030	0.033	0.034	0.034	0.055
QA/QC										
BH-301-14		49.31	196.43	66.25	191.12	83.79	32.13	131.29	31.68	16.43
BH-301-14-DUP		44.60	177.67	60.73	175.39	76.96	29.26	120.80	29.03	15.23
	% Relative Difference	10	10	9	9	8	9	8	9	8
BH-301-22		0.25	1.19	1.09	4.06	1.67	0.32	1.28	0.37	0.38
BH-301-22-DUP		0.20	0.73	0.86	3.21	1.33	0.26	1.02	0.29	0.31
	% Relative Difference	23	**48**	24	23	23	22	22	24	19
BH-302-10		92.86	145.89	69.93	286.65	117.17	63.40	234.89	57.16	26.36
BH-302-10-DUP		76.02	117.83	57.51	237.37	97.01	55.19	195.59	47.57	21.55
	% Relative Difference	20	21	19	19	19	14	18	18	20
BH-302-18		0.80	2.95	0.69	2.50	1.00	0.29	1.15	0.33	0.26
BH-302-18-DUP		3.53	7.70	3.73	11.32	4.59	2.06	7.80	1.97	1.08
	% Relative Difference	**126**	**89**	**137**	**128**	**128**	**151**	**149**	**143**	**122**
BH-302-26		0.83	1.56	0.94	3.12	1.23	0.54	2.09	0.58	0.33
BH-302-26-DUP		0.84	1.53	0.92	3.11	1.26	0.56	2.19	0.57	0.36
	% Relative Difference	0	2	3	0	2	4	4	1	8
BH-303-9		130.82	229.27	175.89	527.71	212.29	107.62	400.64	100.04	46.80
BH-303-9-DUP		3.39	5.50	2.81	9.41	3.83	1.71	6.74	1.79	1.20
	% Relative Difference	**190**	**191**	**194**	**193**	**193**	**194**	**193**	**193**	**190**
BH-304-12		84.62	210.96	65.42	295.36	117.99	63.60	241.19	59.42	25.90
BH-304-12-DUP		87.22	214.60	105.79	319.68	124.50	67.35	255.72	63.50	28.30
	% Relative Difference	3	2	47	8	5	6	6	7	9
BH-304-21		0.54	0.50	1.18	4.73	1.68	0.73	3.00	0.86	0.50
BH-304-21-DUP		0.30	0.17	0.58	2.50	0.83	0.47	1.87	0.52	0.39
	% Relative Difference	**56**	**97**	**69**	**62**	**68**	**44**	**47**	**48**	**25**
BH-401-12		35.7	96.2	55.3	178.6	74.5	29.2	134.9	29.7	9.0
BH-401-12 Dup		34.5	84.7	55.1	175.9	71.6	29.3	131.9	29.9	9.2
	% Relative Difference	4	13	0	2	4	0	2	0	3
BH-401-12		35.7	96.2	55.3	178.6	74.5	29.2	134.9	29.7	9.0
BH-401-12 Dup		34.5	84.7	55.1	175.9	71.6	29.3	131.9	29.9	9.2
	% Relative Difference	4	13	0	2	4	0	2	0	3
BH-401-22		8.4	23.2	16.1	51.6	22.0	7.1	33.1	7.3	2.4
BH-401-22 Dup		7.8	19.1	13.8	43.9	18.3	6.0	27.6	6.2	1.9
	% Relative Difference	8	19	15	16	18	16	18	16	23
BH-401-31		0.1	0.1	1.0	3.8	1.5	0.3	1.1	0.3	0.3
BH-401-31 Dup		0.2	0.2	1.1	3.9	1.5	0.3	1.3	0.3	0.4
	% Relative Difference	**30**	**55**	4	3	4	12	13	10	11
BH-402-10		37.9	85.5	51.6	166.0	65.7	33.0	147.8	32.6	9.2
BH-402-10 Dup		42.9	99.3	61.2	199.3	79.0	40.0	178.5	39.9	11.4
	% Relative Difference	12	15	17	18	18	19	19	20	21
BH-402-19		12.8	26.4	17.5	56.5	22.7	11.0	50.4	11.0	2.8
BH-402-19 Dup		5.4	12.8	8.0	26.9	10.7	4.2	19.9	4.4	1.4
	% Relative Difference	**82**	**69**	**74**	**71**	**72**	**89**	**87**	**85**	**69**
BH-402-30		3.7	8.4	5.3	18.8	7.6	2.8	13.8	3.1	0.9
BH-402-30 Dup		6.7	12.0	7.3	25.0	9.8	3.6	17.3	3.9	1.2
	% Relative Difference	**59**	**35**	**31**	**28**	25	24	23	23	**27**
BH-403-20		0.3	1.46	0.6	2.0	0.8	0.2	1.1	0.3	0.2
BH-403-20 Dup		0.3	1.39	0.6	2.1	0.8	0.2	1.0	0.3	0.2
	% Relative Difference	3	5	1	0	1	2	3	0	2
BH-405-10		6.8	24.2	10.1	34.1	14.7	5.7	25.2	5.6	1.9
BH-405-10 Dup		6.4	22.6	9.9	33.1	14.0	5.6	24.3	5.4	1.9
	% Relative Difference	6	7	2	3	5	2	4	3	3
BH-405-22		0.4	1.8	0.4	1.6	0.6	0.2	0.7	0.2	0.2
BH-405-22 Dup		0.5	1.6	0.6	2.2	0.9	0.3	1.2	0.3	0.3
	% Relative Difference	20	9	**34**	**35**	**30**	**58**	**54**	**55**	**64**
BH-406-21		1.4	2.0	1.5	5.2	2.2	0.9	4.4	1.0	0.3
BH-406-21 Dup		1.7	2.4	1.7	6.0	2.5	1.0	4.9	1.1	0.4
	% Relative Difference	20	18	14	14	14	11	10	9	5

B.3 Groundwater Sample Collection and Analysis

Groundwater samples were collected in the field in 40 mL glass teflon lined screw caped lids using a low-flow peristaltic pump equipped and zero-headspace. Samples were preserved with 0.4 mL 10% sodium azide (v/v) in the field and immediately placed in a cooler with ice and transported back to the Organic Geochemistry Laboratory at the University of Waterloo for analysis. Samples were stored in a refrigerator at 4 oC and analyzed within 14 days of sample collection. Groundwater samples were analyzed for BTEXTMB and TPH using a HP 5890 capillary gas chromatograph (GC) equipped with a HP7673A autosampler and flame ionization detector at the Organic Geochemistry laboratory at the University of Waterloo following the methods of Henderson et al. (1976). Quality Assurance and quality control measures involved collection of duplicate and equipment blanks every 10 samples.

Table B.13: Summary of pre-injection groundwater quality results for BTEXTMB at MW-301.

Sample ID	Sampling Date	Elevation (m AMSL)		Benzene	Toluene	Ethylbenzene	P,M-xylene	O-xylene	Xylenes	1,3,5-Trimethyl-Benzene	1,2,4-Trimethyl-Benzene	1,2,3-Trimethyl-Benzene	Naphthalene	Total
			MDL	**1**	**1**	**1**	**1**	**0**		**1**	**1**	**1**	**2**	**µg/L**
			LOQ	**4**	**3**	**4**	**8**	**5**		**3**	**3**	**4**	**7**	
MW-301-3B	**29-May-08**	**308.5**		77	275	237	913	498	1412	231	521	330	103	1773
-Injection S	**29-May-08**	**307.5**		49	70	46	217	84	301	65	180	127	55	592
MW-301-4B	**29-May-08**			45	70	48	224	84	309	65	181	128	56	593
MW-301-5B	**29-May-08**	**306.5**		124	338	298	1149	337	1487	183	617	241	125	1925
MW-301-6B	**21-Nov-08**	**305.5**		249	491	839	3203	600		352	1346	457	321	4056
MW-301-7B	**30-May-08**	**304.5**		282	885	933	3701	812	4513	407	1602	513	268	4889
MW-301-7B	**21-Nov-08**			274	512	837	3256	442	3698	338	1321	443	279	4004
MW-301-7B	**28-Apr-09**			168	787	1222	4551	457	5009	400	1662	572	333	5143
MW 301-8B	**18-Dec-07**	**303.5**		1549	19427	2704	9655	3958	13613	608	2493	740	511	28032
MW-301-8A	**30-May-08**			347	1083	1194	4727	1107	5835	554	2216	668	419	6481
MW-301-8B	**21-Nov-08**			250	501	1108	4292	812	5104	463	1819	567	345	5052
MW-301-8B	**28-Apr-09**			195	874	1233	4554	624	5177	412	1654	495	308	5170
MW 301-9B	**18-Dec-07**	**302.5**		1510	4856	2148	7877	2867	10744	414	1755	549	370	11603
MW-301-9B	**30-May-08**			662	1802	826	3353	1248	4600	257	1088	395	258	5289
MW-301-9B	**21-Nov-08**			1030	2247	1857	6971	2375	9346	432	1810	584	367	8328
MW-301-9B	**28-Apr-09**			1065	3511	1863	7028	2460	9489	460	1960	656	356	9872
MW 301-10B	**18-Dec-07**	**301.5**		1452	10228	2193	7860	3204	11064	446	1855	559	418	17151
MW-301-10B	**30-May-08**			380	2946	1365	5117	1967	7084	344	1452	481	300	7269
MW-301-10B	**21-Nov-08**			855	2347	1549	5724	1861	7585	360	1511	497	334	7453
MW-301-10A	**28-Apr-09**			535	3395	1839	6614	2128	8742	8742	447	1888	618	17464
MW 301-11B	**18-Dec-07**	**300.5**		1289	15023	1919	6912	2907	9819	385	1594	484	376	21070
MW-301-11B	**30-May-08**			270	872	870	3274	1074	4348	330	1330	447	298	4416
MW-301-11B	**21-Nov-08**			181	753	1081	4150	987	5136	371	1511	484	293	4675
MW-301-11B	**28-Apr-09**			183	759	1285	4726	721	5446	443	1775	584	314	5344
MW 301-12B	**18-Dec-07**	**299.5**		1373	2350	1517	5337	2197	7534	7534	254	1090	360	14478
MW-301-12B	**30-May-08**			2021	6576	2169	8116	2949	11065	461	1970	619	402	14219
MW-301-12B	**21-Nov-08**			1182	2568	1948	7116	2453	9569	389	1676	544	360	8667

LEGEND

0.0 = NOT DETECTED = < MDL

MDL= METHOD DETECTION LIMIT

LOQ= LIMIT OF QUANTIFICATION (3*MDL)

Table B.14: Summary of pre-injection groundwater quality results for BTEXTMB at MW-302.

Sample ID	**Sampling Date**	**Elevation (m AMSL)**		**Benzene**	**Toluene**	**Ethylbenzene**	**P,M-xylene**	**O-xylene**	**Xylenes**	**1,3,5-Trimethyl-Benzene**	**1,2,4-Trimethyl-Benzene**	**1,2,3-Trimethyl-Benzene**	**Naphthalene**	**Total**
			MDL	**1**	**1**	**1**	**1**	**0**		**1**	**1**	**1**	**2**	**µg/L**
			LOQ	**4**	**3**	**4**	**8**	**5**		**3**	**3**	**4**	**7**	
MW-302-5B	**29-May-08**	**306.2**		132	85	571	2816	477	3292	380	1463	499	263	6685
MW-302-5B	**20-Nov-08**			88	1154	629	2942	1122	4064	248	979	368	225	7755
MW-302-5B	**28-Apr-09**			67	177	600	2834	376	3210	396	1596	561	264	6871
MW-302-6B	**29-May-08**	**305.2**		137	138	643	3116	644	3760	423	1626	551	249	7528
MW-302-6B	**20-Nov-08**			322	5369	2344	8964	3443	12407	552	2213	712	481	24401
MW-302-6B	**28-Apr-09**			66	776	670	2967	561	3527	374	1517	534	259	7722
MW-302-7B	**29-May-08**	**304.2**		173	907	899	4124	1121	5245	469	1824	597	273	10387
MW-302-7B	**20-Nov-08**			383	4442	2005	7607	2837	10444	593	2289	708	437	21302
MW-302-7A	**28-Apr-09**			233	970	983	4119	589	4708	577	2255	730	359	10816
MW 302 8B	**18-Dec-07**	**303.2**		2869	9766	1889	7683	2985	10668	467	1929	594	371	28553
MW-302-8B	**29-May-08**			173	907	899	4124	1121	5245	469	1824	597	273	10387
MW-302-8A	**20-Nov-08**			383	4442	2005	7607	2837	10444	593	2289	708	437	21302
MW-302-8B	**28-Apr-09**			218	975	987	4145	594	4739	586	2271	737	359	10872
MW 302 9B	**18-Dec-07**	**302.2**		2333	9929	1884	7479	2987	10467	410	1721	533	345	27621
MW-302-9B	**29-May-08**			3288	6719	1799	7158	2895	10053	417	1830	609	417	25130
MW-302-9B	**20-Nov-08**			3200	8201	2245	8400	3351	11751	517	2132	666	450	29161
MW-302-9B	**28-Apr-09**			1945	6962	2700	10311	3811	14121	735	3324	1058	670	31516
MW 302 10B	**18-Dec-07**	**301.2**		1426	4304	684	2985	1284	4269	155	646	221	139	11844
MW-302-10B	**29-May-08**			2167	4813	1496	6028	2344	8373	392	1700	564	375	19880
MW-302-10B	**28-Apr-09**			1449	4703	2263	8996	3251	12247	604	2676	864	498	25303
MW 302 11B	**18-Dec-07**	**300.2**		2263	6443	1751	7252	2685	9937	475	1968	602	347	13849
MW-302-11B	**29-May-08**			1275	2946	1196	5108	1893	7001	409	1782	594	365	22569
MW-302-11B	**20-Nov-08**			2126	5917	2090	8150	3055	11205	549	2235	707	433	36467
MW-302-11B	**29-Apr-09**			909	2805	1776	7322	2353	9675	616	2584	848	401	29290
MW 302 12B	**18-Dec-07**	**299.2**		1950	4689	1014	5132	1963	7095	310	1251	397	199	9811
MW-302-12B	**29-May-08**			1344	3034	1285	5504	2017	7521	441	1919	639	390	24094
MW-302-12B	**20-Nov-08**			2250	5494	2013	7822	2918	10740	539	2230	698	425	35129
MW-302-12B	**29-Apr-09**			1174	3007	1915	7837	2590	10427	631	2695	868	426	31571
MW 302 13B	**18-Dec-07**	**298.2**		1646	2794	1420	5522	2109	7631	327	1418	463	259	8328
MW-302-13B	**29-May-08**			1251	2377	975	4070	1609	5678	296	1305	437	271	18269
MW-302-13B	**20-Nov-08**			1846	3388	1194	4628	1807	6435	326	1373	429	251	21677
MW-302-13B	**29-Apr-09**			1253	3075	1849	7305	2587	9892	514	2234	720	371	29799

LEGEND

0.0 = NOT DETECTED = < MDL

MDL= METHOD DETECTION LIMIT

LOQ= LIMIT OF QUANTIFICATION (3*MDL)

Table B.15: Summary of pre-injection groundwater quality results for BTEXTMB at MW-303.

Sample ID	Sampling Date	Elevation (m AMSL)		Benzene	Toluene	Ethylbenzene	P,M-xylene	O-xylene	Xylenes	1,3,5-Trimethyl-Benzene	1,2,4-Trimethyl-Benzene	1,2,3-Trimethyl-Benzene	Naphthalene	Total
			MDL	**1**	**1**	**1**	**1**	**0**		**1**	**1**	**1**	**2**	**μg/L**
			LOQ	**4**	**3**	**4**	**8**	**5**		**3**	**3**	**4**	**7**	
MW-303-3B	**30-May-08**	**308.0**		920	453	503	3600	1241	4840.8	514	1751	670	189	9841
MW-303-3B	**28-Apr-09**			408.73	30.81	184.72	1676.21	389.28	2065.5	354.93	680.57	358.69	122.58	4207
MW-303-4B	**28-Apr-09**	**307.0**		668.49	211.24	1012.16	5384.13	661.26	6045.4	579.46	2220.39	808.54	343.04	11889
MW-303-6B	**30-May-08**	**305.0**		2049	4574	1843	6929	2469	9399	758	3025	912	656	23216
MW-303-6A	**21-Nov-08**			1463.97	3024.70	1819.16	7597.75	2530.71	10128.47	611.41	2476.01	767.72	468.47	20760
MW-303-6A	**28-Apr-09**			793.31	712.39	1728.58	7657.80	2094.45	9752.26	636.00	2718.53	888.39	434.31	17664
MW-303-7B	**30-May-08**	**304.0**		2766	6837	1539	6320	2370	8689.40	436	1746	564	329	22905
MW-303-7B	**21-Nov-08**			1795.78	5431.53	1903.37	7887.99	2861.73	10749.72	640.10	2578.68	791.20	493.84	24384
MW-303-7A	**29-Apr-09**			662.33	3218.95	3445.71	13129.41	4612.39	17741.80	1486.66	6632.42	2052.03	1206.14	36446
MW 303-10B	**18-Dec-07**	**301.0**		1117.4	2948.4	1262.3	5108.3	1714.0	6822.3	375.1	1553.8	479.3	272.6	14831
MW-303-10B	**30-May-08**			272	1005	985	4586	1484	6070	513	2173	693	86	11797
MW-303-10B	**21-Nov-08**			486.24	1666.09	1439.40	6245.00	1863.61	8109	574.34	2345.89	730.61	391.01	15742
MW-303-10A	**29-Apr-09**			271.66	689.23	1156.75	5067.29	1379.24	6447	541.82	2207.91	714.74	302.01	12331
MW 303-11B	**18-Dec-07**	**300.0**		482.6	1100.6	1118.2	4498.0	1472.9	5971.0	381.9	1587.8	493.2	265.0	11400
MW-303-11B	**30-May-08**			163	324	1083	5024	1527	6551	627	2564	779	334	12425
MW-303-11B	**21-Nov-08**			276.61	803.03	1446.22	6203.28	1782.54	7986	630.68	2596.02	791.84	421.22	14951
MW-303-11B	**29-Apr-09**			101.41	358.27	1076.22	4858.85	1288.52	6147	640.42	2706.49	847.89	349.23	12227

LEGEND

0.0 = NOT DETECTED = < MDL

MDL= METHOD DETECTION LIMIT

LOQ= LIMIT OF QUANTIFICATION (3*MDL)

Table B.15: Summary of pre-injection groundwater quality results for BTEXTMB at MW-303.

Sample ID	**Sampling Date**	**Elevation (m AMSL)**		**Benzene**	**Toluene**	**Ethylbenzene**	**P,M-xylene**	**O-xylene**	**Xylenes**	**1,3,5-Trimethyl-Benzene**	**1,2,4-Trimethyl-Benzene**	**1,2,3-Trimethyl-Benzene**	**Naphthalene**	**Total**
			MDL	**1**	**1**	**1**	**1**	**0**		**1**	**1**	**1**	**2**	**µg/L**
			LOQ	**4**	**3**	**4**	**8**	**5**		**3**	**3**	**4**	**7**	
MW 304-7B	**18-Dec-07**	**304.0**		1334	4939	1747	7124	2670	9794	532	2268	688	399	21702
MW-304-7B	**29-May-08**			458	1942	1301	5963	2234	8197	526	2171	695	370	23856
MW-304-7B	**20-Nov-08**			817	2731	2065	8799	3316	12116	665	2768	882	476	34635
MW-304-7B	**28-Apr-09**			320	1685	1702	7272	2403	9674	665	2822	916	412	27870
MW-304-8B	**29-May-08**	**303.0**		321	3073	1155	5507	2185	7692	496	2065	681	381	23556
MW-304-8B	**20-Nov-08**			344	2239	757	3542	1223	4765	466	1809	565	266	15976
MW-304-8A	**20-Nov-08**			330	2267	757	3503	1205	4708	443	1719	545	286	15764
MW-304-8B	**28-Apr-09**			423	2750	1356	5719	2061	7780	687	2941	939	550	25205
MW 304-9B	**18-Dec-07**	**302.0**		1305	4810	1546	6447	2390	8837	489	2068	632	339	20025
MW-304-9B	**29-May-08**			241	1173	1113	5388	1946	7334	479	1990	655	333	20653
MW-304-9B	**20-Nov-08**			449	1320	1430	6466	2201	8666	643	2583	812	389	24958
MW-304-9B	**28-Apr-09**			262	862	1518	6692	2006	8698	741	3113	977	427	25298
MW 304-10B	**18-Dec-07**	**301.0**		2591	4713	1825	7196	2659	9854	491	2079	633	355	22541
MW-304-10B	**29-May-08**			488	1922	1408	6561	2292	8853	607	2450	773	378	25732

LEGEND
0.0 = NOT DETECTED = < MDL
MDL= METHOD DETECTION LIMIT
LOQ= LIMIT OF QUANTIFICATION (3*MDL)

Table B.17 Summary of soil coring comparision of the results of duplicate samples for QA/QC.

			Benzene	**Toluene**	**Ethylbenzene**	**P,M-xylene**	**O-xylene**	**TMB-1,3,5**	**TMB-1,2,4**	**TMB-1,2,3**	**Naphthalene**
Sample ID QA/QC			**0.032**	**0.028**	**0.036**	**0.058**	**0.030**	**0.033**	**0.034**	**0.034**	**0.055**
MW 304-10B	**18-Dec-07**		2591	4713	1825	7196	2659	491	2079	633	355
MW 304-10B	**18-Dec-07**		1950	3779	1258	5032	1952	313	1342	429	256
		% Relative Difference	28	22	37	35	31	44	43	39	32
MW 301-8B	**18-Dec-07**		1522	19109	2690	9551	3942	613	2482	735	468
MW 301-8B	**18-Dec-07**		1478	18022	2717	9741	3927	624	2555	751	507
		% Relative Difference	3	6	1	2	0	2	3	2	8
MW 302 8B	**18-Dec-07**		2869	9766	1889	7683	2985	467	1929	594	371
MW 302 8B	**18-Dec-07**		2769	9460	1819	7387	2860	467	1916	585	368
		% Relative Difference	4	3	4	4	4	0	1	2	1
MW-301-9B	**30-May-08**		662	1802	826	3353	1248	257	1088	395	258
MW-301-9B	**30-May-08**		889	2309	948	3807	1456	271	1169	420	281
		% Relative Difference	29	25	14	13	15	5	7	6	9
MW-302-13B	**29-May-08**		1251	2377	975	4070	1609	296	1305	437	271
MW-302-13B	**29-May-08**		1497	2959	1323	5544	2101	412	1796	584	350
		% Relative Difference	18	22	30	31	27	33	32	29	25
MW-303-4B	**30-May-08**		771	473	464	3635	1201	358	1387	504	166
MW-303-4B	**30-May-08**		777	482	492	3739	1241	364	1434	518	194
		% Relative Difference	1	2	6	3	3	2	3	3	16
MW-304-9B	**29-May-08**		241	1173	1113	5388	1946	479	1990	655	333
MW-304-9B	**29-May-08**		308	933	1423	6634	2208	610	2517	788	387
		% Relative Difference	24	23	24	21	13	24	23	18	15
MW-301-12B	**21-Nov-08**	12	1182	2568	1948	7116	2453	389	1676	544	360
MW-301-12B	**21-Nov-08**	12	1137	2478	1850	6762	2338	364	1572	514	342
		% Relative Difference	4	4	5	5	5	7	6	6	5
MW-302-8A	**20-Nov-08**	8	1079	6653	1934	7490	2793	484	1991	624	397
MW-302-8B	**20-Nov-08**	8	1211	7086	1945	7500	2795	479	1926	613	403
		% Relative Difference	12	6	1	0	0	1	3	2	1
MW-303-6A	**21-Nov-08**		1464	3025	1819	7598	2531	611	2476	768	468
MW-303-6B	**21-Nov-08**		1521	3075	1949	8035	2663	670	2714	829	460
		% Relative Difference	4	2	7	6	5	9	9	8	2
MW-304-8A	**20-Nov-08**		330	2267	757	3503	1205	443	1719	545	286
MW-304-8B	**20-Nov-08**		344	2239	757	3542	1223	466	1809	565	266
		% Relative Difference	4	1	0	1	1	5	5	4	7
MW-301-10B	**28-Apr-09**		470	2715	1510	5493	1667	399	1642	550	316
MW-301-10A	**28-Apr-09**		535	3395	1839	6614	2128	447	1888	618	375
		% Relative Difference	13	22	20	19	24	11	14	12	17
MW-302-7A	**28-Apr-09**		233	970	983	4119	589	577	2255	730	359
MW-302-7A	**28-Apr-09**		218	975	987	4145	594	586	2271	737	359
		% Relative Difference	6	0	0	1	1	1	1	1	0
MW-303-3B	**28-Apr-09**		409	31	185	1676	389	355	681	359	123
MW-303-3A	**28-Apr-09**		391	31	193	1696	368	339	720	343	131
		% Relative Difference	4	0	4	1	6	4	6	4	7
MW-304-5B	**28-Apr-09**		289	3304	1475	6816	2547	842	3401	1074	470
MW-304-5A	**28-Apr-09**		261	2551	1173	5497	2065	713	2812	905	384
		% Relative Difference	10	26	23	21	21	17	19	17	20
Equipment Blanks											
MW-301-E1B	**30-May-08**		0	2	1	7	2	0	3	0	0
MW-301-E1B	**30-May-08**		0	2	1	7	2	0	3	0	0
MW-302-E2B	**29-May-08**		0	1	0	4	0	0	1	0	0
MW-303-E3B	**30-May-08**		4	8	3	13	4	0	4	1	0
MW-303-E33B	**30-May-08**		1	3	3	18	6	1	5	2	0
MW-304-E4B	**29-May-08**		0	3	2	13	4	1	6	2	2
MW-302-E2B	**20-Nov-08**		0	21	0	0	0	0	0	0	0

Appendix C

Microcosm Experiment

Table C.1 Initial composition of organic consituents in microcosm test solution, batches A and B

ORGANIC GEOCHEMISTRY LABORATORY
Client: Dale Holtze Denitrification Experiment
Laboratory Number: 100503, 100504, 100505, 100508, 100509
BTEX, Trimethylbenzenes ,Naphthalene Analysis (Using Peak Simple Data Integration software)
Samples submitted: May 12 to May 25, 2010
Analysis occurred: May13, May 17, May 18, May 25, 2010
Analyst: Marianne VanderGriendt
Report Date: May 31, 2010

LEGEND
0.0 = NOT DETECTED = < MDL
MDL= METHOD DETECTION LIMIT
LOQ= LIMIT OF QUANTIFICATION (3*MDL)
GC repeat = Gas Chromatographic Repeat
Extraction Duplicate = Method Extraction Duplicate from the same sample
Field Duplicate = Method Extraction of Field Duplicate

Units are µg/L (ppb)

Sample ID	Date		Benzene	Toluene	Ethylbenzene	P,M-xylene	O-xylene	1,3,5-Trimethyl-Benzene	1,2,4-Trimethyl-Benzene	1,2,3-Trimethyl-Benzene	Naphthalene	Total BTEXTMB	*F1 Fraction*	*F2 Fraction*	*F3 Fraction*	Total TPH
		MDL (Oct 2009)	1.11	0.83	0.77	1.46	0.37	0.74	0.82	0.76	2.20					
		LOQ	3.34	2.49	2.32	4.38	1.11	2.21	2.47	2.28	6.61					
Control Initial Mix	**11-May-10**		186	1214	1268	5012	1674	436	1836	552	282	**12274**	**16724**	**4443**	**141**	**21308**
Active Initial Mix	**11-May-10**		196	1231	1303	5139	1725	460	1936	579	296	**12668**	17288	5036	305	**22629**
Start Batch A - Active-1	**11-May-10**		167	1233	1282	5100	1708	440	1843	564	347	**12518**	**16680**	**4059**	**144**	**20883**
Start Batch A - Active-2	**11-May-10**		166	1223	1274	5063	1697	438	1835	560	346	**12437**	16585	4113	118	**20816**
End Batch A - Active-3	**11-May-10**		134	900	981	3689	1342	400	1763	510	270	**9856**	14337	7419	965	**22721**
End Batch A - Active-4	**11-May-10**		119	713	770	2866	1047	312	1384	394	215	**7701**	11375	6161	926	**18462**
Start Batch B - Control-1	**11-May-10**		160	1202	1244	4947	1654	425	1776	543	335	**12126**	16131	3828	106	**20064**
Start Batch B - Control-2	**11-May-10**		164	1217	1262	5015	1678	431	1803	552	342	**12299**	16370	3896	78	**20345**
End Batch B - Control-3	**11-May-10**		158	1228	1274	5077	1698	436	1823	560	346	**12443**	16570	3980	73	**20623**
End Batch B - Control-4	**11-May-10**		159	1198	1241	4945	1652	425	1779	545	338	**12123**	16170	3891	130	**20191**
	Avg Start Batch A		167	1228	1278	5081	1703	439	1839	562	346	12477	16633	4086	131	20850
	Stdev Start Batch A		0.4	6.6	6.0	25.7	7.9	1.4	5.9	2.9	0.9	57.3	67.1	38.4	18.5	47.2
	Avg End Batch A		126	807	875	3278	1194	356	1574	452	243	8778	12856	6790	946	20592
	Stdev End Batch A		10.6	132.2	149.3	581.6	208.8	62.2	268.3	81.9	39.2	1523.6	2094.4	889.4	28.1	3011.9
	% difference Batch A		24%	34%	32%	35%	30%	19%	14%	20%	30%	30%	23%	66%	624%	1%
	Avg Start Batch B		162	1210	1253	4981	1666	428	1789	548	339	12213	16251	3862	92	20205
	Stdev Start Batch B		2.5	10.5	13.0	47.6	16.6	4.0	19.5	6.1	5.0	122.3	169.4	48.3	19.5	198.2
	Avg End Batch B		159	1213	1258	5011	1675	430	1801	552	342	12283	16370	3936	101	20407
	Stdev End Batch B		0.2	21.5	23.3	93.5	32.7	7.8	31.3	10.7	5.8	226.7	282.5	63.0	40.5	304.9
	% difference Batch B		2.1%	0.3%	0.4%	0.6%	0.6%	0.5%	0.7%	0.9%	1.1%	0.6%	0.7%	1.9%	9.9%	1.0%

Table C.2 Composition of organic consituents in the Control Microcosm Treatment replicates over time.

ORGANIC GEOCHEMISTRY LABORATORY
Client: Dale Holtze Denitrification Experiment
Laboratory Number: 100503, 100504, 100505, 100508, 100509
BTEX, Trimethylbenzenes ,Naphthalene Analysis (Using Peak Simple Data Integration software)
Samples submitted: May 12 to May 25, 2010
Analysis occurred: May13, May 17, May 18, May 25, 2010
Analyst: Marianne VanderGriendt
Report Date: May 31, 2010

LEGEND
0.0 = NOT DETECTED = < MDL
MDL= METHOD DETECTION LIMIT
LOQ= LIMIT OF QUANTIFICATION (3*MDL)
GC repeat = Gas Chromatographic Repeat
Extraction Duplicate = Method Extraction Duplicate from the same sample
Field Duplicate = Method Extraction of Field Duplicate

Units are µg/L (ppb)

Sample ID	Date		Benzene	Toluene	Ethylbenzene	P,M-xylene	O-xylene	1,3,5-Trimethyl-Benzene	1,2,4-Trimethyl-Benzene	1,2,3-Trimethyl-Benzene	Naphthalene	Total BTEXTMB mg/L	*F1 Fraction*	*F2 Fraction*	*F3 Fraction*	Total TPH mg/L
		MDL (Oct 2009)	1.11	0.83	0.77	1.46	0.37	0.74	0.82	0.76	2.20					
		LOQ	3.34	2.49	2.32	4.38	1.11	2.21	2.47	2.28	6.61					
Con-1A	**12-May-10**		100	1045	1060	4245	1454	355	1508	479	299	**10.4**	13513	3149	46	**16.7**
Con-1B	**12-May-10**		109	1077	1097	4387	1490	367	1548	488	299	**10.8**	13969	3289	68	**17.3**
Con-1C	**12-May-10**		108	1066	1088	4364	1473	367	1547	484	295	**10.7**	13943	3251	34	**17.2**
Con-2A	**14-May-10**		91	1032	1044	4173	1429	346	1469	466	292	**10.3**	13193	3095	83	**16.4**
Con-2B	**14-May-10**		95	1085	1099	4383	1504	365	1541	490	305	**10.8**	13865	3206	77	**17.1**
Con-2C	**14-May-10**		95	1078	1096	4368	1493	363	1527	485	298	**10.7**	13807	3165	52	**17.0**
Con-3A	**18-May-10**		106	1104	1100	4374	1495	361	1516	480	299	**10.7**	13949	3296	69	**17.3**
Con-3B	**18-May-10**		103	1085	1088	4330	1475	358	1498	472	293	**10.6**	13789	3206	59	**17.1**
Con-3C	**18-May-10**		102	1117	1114	4428	1509	364	1526	482	295	**10.8**	14064	3269	67	**17.4**
Con-5A	**25-May-10**	**Extracted Immediately**	93	1053	1050	4177	1434	336	1427	453	258	**10.2**	13183	2952	82	**16.2**
Con-5B	**25-May-10**		96	1090	1086	4316	1481	349	1479	469	270	**10.5**	13636	3011	26	**16.7**
Con-5C	**25-May-10**		92	1081	1078	4296	1466	344	1465	463	268	**10.5**	13510	2971	36	**16.5**
Con 6A	**1-Jun-10**	**Extracted the same day**	74	959	952	3804	1307	299	1285	410	229	**9.2**	11875	2562	30	**14.5**
Con 6B	**1-Jun-10**		81	967	961	3801	1331	305	1301	419	240	**9.3**	12008	2586	44	**14.6**
Con 6C	**1-Jun-10**		81	960	954	3796	1308	301	1290	411	230	**9.2**	11934	2582	42	**14.6**
Con-6C Repeat	**8-Jun-10**		81	962	1000	3975	1384	325	1388	445	262	**9.7**	12475	2521	75	**15.1**
Con 7A	**8-Jun-10**	**Extracted same day**	101	1092	1069	4254	1469	330	1422	456	244	**10.3**	13340	2799	40	**16.2**
Con 7B	**8-Jun-10**		107	1106	1087	4321	1493	336	1453	466	255	**10.5**	13596	2895	37	**16.5**
Con 7C	**8-Jun-10**		105	1082	1066	4242	1466	332	1432	459	250	**10.3**	13360	2849	26	**16.2**
Con 8A	**6-Jul-10**	**Extracted the same day**	100	1058	1035	4079	1448	316	1363	445	230	**10.0**	12844	2690	35	**15.6**
Con 8B	**6-Jul-10**		98	1070	1047	4115	1465	322	1383	452	234	**10.1**	12981	2777	39	**15.8**
Con 8C	**6-Jul-10**		97	1053	1030	4028	1456	317	1367	452	236	**9.9**	12763	2751	21	**15.5**

Table C.3 Composition of organic consituents in the Active Microcosm Treatment replicates over time.

ORGANIC GEOCHEMISTRY LABORATORY
Client: Dale Holtze Denitrification Experiment
Laboratory Number: 100503, 100504, 100505, 100508, 100509
BTEX, Trimethylbenzenes ,Naphthalene Analysis (Using Peak Simple Data Integration software)
Samples submitted: May 12 to May 25, 2010
Analysis occurred: May13, May 17, May 18, May 25, 2010
Analyst: Marianne VanderGriendt
Report Date: May 31, 2010

LEGEND
0.0 = NOT DETECTED = < MDL
MDL= METHOD DETECTION LIMIT
LOQ= LIMIT OF QUANTIFICATION (3*MDL)
GC repeat = Gas Chromatographic Repeat
Extraction Duplicate = Method Extraction Duplicate from the same sample
Field Duplicate = Method Extraction of Field Duplicate

Units are µg/L (ppb)

Sample Identification	Date		Benzene	Toluene	Ethylbenzene	P,M-xylene	O-xylene	1,3,5-Trimethyl-Benzene	1,2,4-Trimethyl-Benzene	1,2,3-Trimethyl-Benzene	Naphthalene	Total BTEXTMB mg/L	*F1 Fraction*	*F2 Fraction*	*F3 Fraction*	Total TPH mg/L
		MDL (Oct 2009)	1.11	0.83	0.77	1.46	0.37	0.74	0.82	0.76	2.20					
		LOQ	3.34	2.49	2.32	4.38	1.11	2.21	2.47	2.28	6.61					
Act-1A	**12-May-10**		106.6	973.8	1011.8	4079.5	1403.2	367.5	1555.7	487.2	317.7	**10.2**	13313.4	3587.7	62.6	**17.0**
Act-1B	**12-May-10**		109.1	986.5	1025.2	4136.8	1424.6	371.3	1572.8	495.9	321.3	**10.3**	13523.5	3579.7	55.2	**17.2**
Act-1C	**12-May-10**		109.4	973.3	1006.9	4063.0	1405.8	364.9	1547.3	489.1	319.8	**10.2**	13310.0	3576.3	50.5	**16.9**
Act-2A	**14-May-10**		106.2	938.2	401.8	4088.0	1419.6	373.3	1571.2	498.7	325.7	**9.6**	12404.6	3644.7	116.6	**16.2**
Act-2B	**14-May-10**		102.1	927.6	318.1	4091.0	1424.6	374.9	1569.5	500.9	326.1	**9.5**	12269.1	3633.3	108.4	**16.0**
Act-2C	**14-May-10**		114.4	963.8	411.6	4200.2	1460.5	386.8	1627.1	513.8	289.1	**9.9**	12833.1	3842.5	144.7	**16.8**
Act-3A	**18-May-10**		81.8	210.7	7.2	3525.8	1362.9	384.0	1493.6	500.8	260.3	**7.7**	10331.0	3538.0	115.6	**14.0**
Act-3B	**18-May-10**		82.0	230.3	20.1	3453.3	1343.3	377.6	1472.2	494.7	247.9	**7.6**	10214.7	3670.0	173.0	**14.1**
Act-3C	**18-May-10**		91.6	325.3	72.8	3636.2	1370.5	386.3	1518.6	503.3	259.0	**8.1**	10756.1	3560.4	184.2	**14.5**
Act-5A	**25-May-10**		69.2	49.3	5.4	3289.5	1322.9	377.5	1412.3	485.9	119.1	**7.1**	9617.2	3037.3	28.8	**12.7**
Act-5B	**25-May-10**		67.6	52.9	11.0	3017.0	1284.8	377.6	1300.9	482.7	82.5	**6.6**	9051.5	2934.4	50.0	**12.0**
Act-5C	**25-May-10**		60.9	47.9	31.8	2869.3	1251.8	368.2	1286.0	476.1	138.5	**6.5**	8756.1	3026.9	35.0	**11.8**
Act 6A	**1-Jun-10**		74.8	57.9	21.5	2435.5	1092.5	348.5	998.6	431.7	11.0	**5.4**	7736.8	3032.8	195.2	**11.0**
Act 6B	**1-Jun-10**		69.0	50.0	0.0	3056.3	1216.1	350.3	1226.5	447.0	34.0	**6.4**	8835.2	2799.7	119.5	**11.8**
Act 6C	**1-Jun-10**		50.1	27.4	3.5	1531.4	904.1	303.1	657.8	389.6	35.6	**3.9**	5348.3	2353.0	60.0	**7.8**
Act 7A	**8-Jun-10**		70.0	43.3	2.4	2891.4	1144.6	363.6	955.2	452.9	8.8	**5.9**	8152.0	2697.4	42.2	**10.9**
Act 7B	**8-Jun-10**		70.2	34.1	0.0	2350.4	1122.7	367.6	936.2	451.7	0.0	**5.3**	7479.4	2808.6	60.9	**10.3**
Act 7C	**8-Jun-10**		72.9	38.2	2.4	2853.3	1219.3	372.0	1167.3	467.5	15.2	**6.1**	8573.5	2816.6	48.4	**11.4**
Act 8A	**6-Jul-10**		0.0	0.0	0.0	4.1	2.2	0.0	0.0	7.9	0.0	**0.0**	63.7	50.8	14.5	**0.1**
Act 8B	**6-Jul-10**		0.0	0.0	0.0	3.4	1.8	0.0	0.8	8.4	0.0	**0.0**	76.5	233.8	51.2	**0.4**
Act 8C	**6-Jul-10**		34.5	0.0	0.0	171.7	273.1	148.8	9.1	156.1	1.4	**0.8**	1402.8	1129.3	28.1	**2.6**

Table C.4 Composition of organic consituents in the Active Acetylene Microcosm Treatment replicates over time.

ORGANIC GEOCHEMISTRY LABORATORY
Client: Dale Holtze Denitrification Experiment
Laboratory Number: 100503, 100504, 100505, 100508, 100509
BTEX, Trimethylbenzenes ,Naphthalene Analysis (Using Peak Simple Data Integration software)
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Analyst: Marianne VanderGriendt
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LEGEND
0.0 = NOT DETECTED = < MDL
MDL= METHOD DETECTION LIMIT
LOQ= LIMIT OF QUANTIFICATION (3*MDL)
GC repeat = Gas Chromatographic Repeat
Extraction Duplicate = Method Extraction Duplicate from the same sample
Field Duplicate = Method Extraction of Field Duplicate

Units are μg/L (ppb)

Sample Identification	Date		Benzene	Toluene	Ethylbenzene	P,M-xylene	O-xylene	1,3,5-Trimethyl-Benzene	1,2,4-Trimethyl-Benzene	1,2,3-Trimethyl-Benzene	Naphthalene	Total BTEXTMB mg/L	*F1 Fraction*	*F2 Fraction*	*F3 Fraction*	Total TPH
		MDL (Oct 2009)	**1.11**	**0.83**	**0.77**	**1.46**	**0.37**	**0.74**	**0.82**	**0.76**	**2.20**					
		LOQ	**3.34**	**2.49**	**2.32**	**4.38**	**1.11**	**2.21**	**2.47**	**2.28**	**6.61**					
Acetylene-1A	**12-May-10**		112.1	1122.1	1139.2	4555.6	1549.4	384.2	1617.6	507.8	311.0	**11.2**	14589.9	3523.1	42.0	**18.2**
Acetylene-1B	**12-May-10**		107.8	1076.7	1096.0	4381.8	1490.1	370.8	1558.8	488.4	299.7	**10.8**	14053.0	3425.0	61.0	**17.5**
Acetylene-1C	**12-May-10**		110.9	1092.4	1107.2	4418.1	1510.2	372.4	1572.2	495.0	308.6	**10.9**	14181.9	3463.3	70.6	**17.7**
Acetylene-2A	**14-May-10**		95.9	1045.9	379.5	4306.7	1491.4	364.8	1517.4	486.8	300.0	**9.9**	12615.5	3226.4	101.6	**15.9**
Acetylene-2B	**14-May-10**		105.1	1098.4	467.6	4519.6	1561.9	384.6	1604.5	512.5	316.8	**10.5**	13377.1	3437.9	79.5	**16.9**
Acetylene-2C	**14-May-10**		112.6	1097.8	583.6	4491.6	1547.7	382.4	1595.1	507.4	313.7	**10.5**	13502.6	3407.6	108.1	**17.0**
Acetylene-3A	**18-May-10**		89.4	591.1	6.1	3911.1	1495.6	363.8	1279.7	483.9	259.2	**8.4**	10887.9	3112.9	90.1	**14.1**
Acetylene-3B	**18-May-10**		81.9	503.1	26.1	3794.3	1449.3	358.5	1334.8	474.9	241.9	**8.2**	10677.8	3077.6	89.3	**13.8**
Acetylene-3C	**18-May-10**		87.8	628.4	33.7	3998.0	1500.6	363.3	1329.0	483.9	263.6	**8.6**	11137.3	3081.0	111.4	**14.3**
Acetylene-5A	**25-May-10**		52.7	133.7	7.1	3278.1	1328.1	319.2	1166.8	437.7	191.9	**6.9**	8888.2	2539.5	39.6	**11.5**
Acetylene-5B	**25-May-10**		76.3	392.4	17.6	3726.5	1376.1	322.3	1249.6	440.9	213.9	**7.7**	10038.4	2623.9	37.6	**12.7**
Acetylene-5C	**25-May-10**		66.5	257.4	10.9	3529.8	1347.6	316.2	1210.7	434.3	202.2	**7.3**	9481.7	2560.2	33.3	**12.1**
C2H2 6A	**1-Jun-10**		27.7	34.3	1.6	1896.3	979.6	252.4	437.5	320.3	5.1	**3.9**	5291.5	1574.9	70.6	**6.9**
C2H2 6B	**1-Jun-10**		2.8	2.5	0.0	3.4	4.4	1.8	0.0	1.0	0.0	**0.0**	94.8	258.6	144.8	**0.5**
C2H2 6C	**1-Jun-10**		0.0	0.0	3.3	1.1	0.0	1.4	1.2	0.0	0.8	**0.0**	137.9	163.1	64.1	**0.4**
C2H2 7A	**8-Jun-10**		89.9	302.5	5.6	3843.4	1416.6	323.7	1267.3	449.5	205.1	**7.8**	10161.1	2686.0	69.4	**12.9**
C2H2 7B	**8-Jun-10**		68.4	162.5	5.5	3565.2	1359.1	303.6	1189.3	434.1	194.9	**7.2**	9299.3	2491.3	56.7	**11.8**
C2H2 7C	**8-Jun-10**		25.8	24.9	0.0	795.6	691.4	195.2	180.8	254.9	0.0	**2.1**	9411.2	2572.0	58.0	**12.0**
C2H2 8A	**6-Jul-10**		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	16.2	21.1	25.5	**0.1**
C2H2 8B	**6-Jul-10**		3.9	0.0	0.0	1.1	1.0	1.0	0.9	0.0	0.0	**0.0**	92.9	198.7	110.4	**0.4**
C2H2 8C	**6-Jul-10**		64.8	48.2	0.0	3209.1	1286.1	293.7	987.3	410.7	38.0	**6.3**	8341.1	1989.0	48.7	**10.4**

Appendix D

Remediation Tracer Test Procedure

D.1 Pre-Injection Groundwater Monitoring and Sampling

Groundwater samples were collected within the monitoring network of the pilot-scale area prior to each injection in order to establish background conditions. Groundwater samples were collected routinely from the discontinuous screened multilevel well MW-302 (ports 5, 6, 7, 8, 9), continuous screened multilevel wells MW-401, MW-402 (ports 1 – 9) and the injection well MW-501. Groundwater samples were collected using well dedicated LDPE tubing and peristaltic pumps for the multilevel wells and Waterra equipped with a foot valve for the 0.051 ID injection well. Bromide analysis was conducted on each of the groundwater samples, with select samples being analyzed for anions of interest. Groundwater elevations were collected from the SNC Lavalin monitoring wells located on Site prior to the injection to establish groundwater flow directions and natural gradients.

D.2 Test Solution Preparation

A 2052 L (550 gal) carboy located within the building out of direct sunlight was nearly filled with municipal water in advance to the date of the injection. The test solution was amended with a conservative tracer bromide in the form of sodium bromide (NaBr) , a reactant nitrate in the form of laboratory grade sodium nitrate (NaNO3) to desired concentrations (listed in Table D.1) and sodium thiosulphate (NaS_2O_5) to de-chlorinate the water supply. 18 mg/L NaS_2O_3 dechlorinates approximately 5 mg/L chlorine. The test solution was prepared in the carboy by adding the test solutes to the water agitated by the drill mixer, which served to readily distribute the additives within the large volume of water. The test solution was sparged with N_2 for approximately 1 hour, in which the dissolved oxygen level was reduced to < 1 mg/L as required to limit the preferential use of O_2 as an electron acceptor in the subsurface environment . A centrifugal pump was used to re-circulate the contents of the carboy to further mix the test solution. The test solution was homogenized by the N_2 sparging and the recirculation of the water through the centrifugal pump, respectively.

Table D.1: Remedial Tracer Test details and injection schedule.

Injection No.	Date	Volume Injected (L)	Br^- Tracer Concentration (mg/L)	NO_3^- Reactant Concentration (mg/L)	Test Solution Temperature (^oC)	Dissolved Oxygen (mg/L)
1	28-Jul-09	2063	200	90	20.1	<1
2	05-Aug-09	2070	200	90	19.2	<1
3	07-Aug-09	2092	200	90	19.8	<1
4	10-Aug-09	2131	200	90	20.2	<1
5	13-Aug-09	2094	200	90	20.4	<1
6	17-Aug-09	2128	200	90	23.2	<1
7	25-Aug-09	2102	200	200	19.7	<1
8	09-Sep-09	2108	200	200	19.2	<1
9	24-Sep-09	*2051*	200	200	-	<1
10	15-Oct-09	2076	200	200	-	<1
11	03-Nov-09	1950	200	200	-	<1
12	18-Nov-09	2017	200	265	10	3

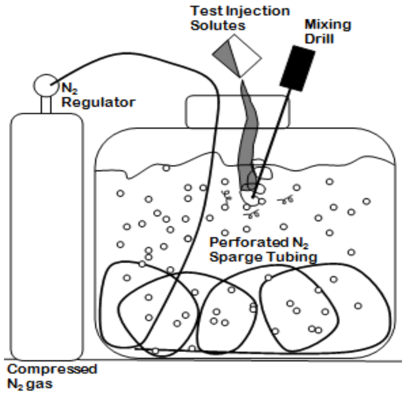


Figure D.1: Preparation of remedial tracer test solution.

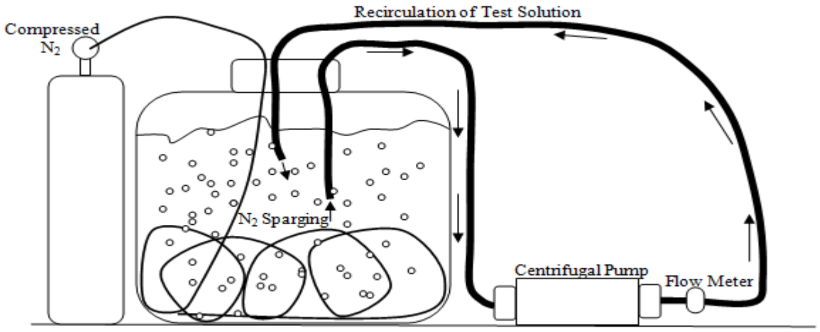


Figure D.2: Mixing of remedial tracer test solution in order to homogenize sample prior to injection.

D.3 Test Setup

The test solution was introduced into the subsurface across a 2 m screen interval in injection well MW-501. A centrifugal pump was used to deliver the prepared test solution from the carboy to the 2” injection well using a 1.5” diameter dense polyethylene tube. The tube was fastened to the injection well containing a casing well fixture equipped with a vent and pressure gage to monitor and mitigate aquifer refusal. A flow meter volumetric reading was recorded prior to the initiation of the pump. A pumping rate of 33-37 L/min was established using the flow meter for the duration of the injection period. Test solution subsamples were collected from the carboy at the start of the test, 30 min into the injection and at the end of the injection, approximately 1 hour after pumping began and analyzed for tracer and reactant in order to evaluate the homogeneity of the test solution and account for changes in desired concentrations related to density effects. Groundwater elevations were measured in the network of monitoring wells throughout the duration of the injection phase with water level tapes (MW-401 and MW-402) and Solinst pressure transducers in the injection well MW-501.

Water levels were monitored periodically with a water level tape (88 minutes post-injection) and continuously using down hole pressure transducers (MW-501 and MW-603) following the completion of the injection phase for 24 hours

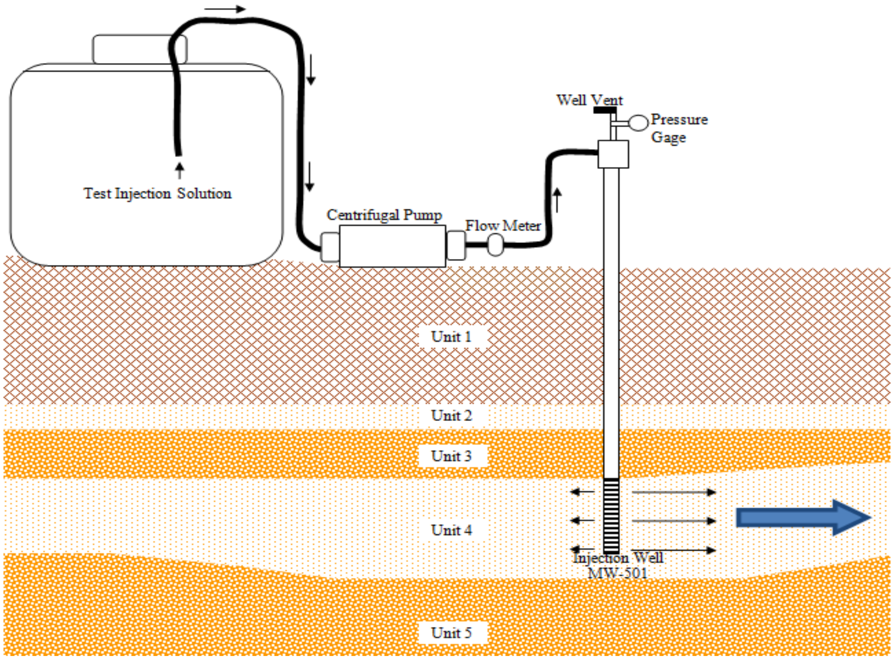


Figure D.3: Cross-sectional view of remediation injection test schematic.

D.4 Test Take-Down

The centrifugal pump was turned off upon completion of the injected test solution. The final measurement of the flow meter volumetric content was recorded to determine the volume of test solution pumped into the aquifer. The PVC tubing was disconnected at the centrifugal pump, with the remainder of the test contents caught within the section of tubing and the well fed by gravitational forces into the well as the tube was elevated. Once the remaining test solution was delivered to the injection well, the tubing was disconnected from the well casing and the fixture was removed.

D.5 Post-Injection Groundwater Sampling

Groundwater samples were collected from injection well MW-501, upgradient well MW-301 (ports 7, 8, 9) and downgradient wells in Row 1: MW-302 (Ports 5-9), MW-401 and MW-402 (Ports 1-9) and Row 2: MW-403, MW-404, MW-405 and MW-406 (Ports 1-9). The groundwater sampling regime was frequent in the early time following the injection phase and diminished with time. A total of 1745 groundwater samples were collected and analyzed for bromide throughout a 143 day period during which 12 injections took place and monitoring continued 26 days following the last injection.

Groundwater samples were collected using well dedicated low density polyethylene (LDPE) tubing and peristaltic pumps for the multilevel wells and Waterra equipped with a foot-valve for the injection well. Prior to groundwater sampling, approximately 0.25 L of groundwater was purged prior to the collection of each sample in the multilevel wells and 5 L for the injection well. Groundwater samples were collected in 25 mL plastic screw cap scint vials. The number of sample vials collected per well port depended on the analyte of interest. In general, 3 20 mL samples were collected per sampling port leaving approximately 5 mL of headspace to aerate the sample and limit the potential for nitrate degradation to occur post-sampling. Samples were immediately placed in a cooler with ice and transported back to the Organic Geochemistry Laboratory at the University of Waterloo and stored accordingly for the analysis of interest. Multilevel sampler wells situated in and around the injection zone were sampled approximately 1 hour following the injection in order to delineate the initial distribution of the tracer slug within the subsurface. Groundwater samples were also collected during the injection phase of the final tracer test in order to establish the first arrival of the injected remedial solution.

D.5.1 Injection Well and Row 1

Groundwater sampling frequency was as high as 1 hr, 4 hrs, 8 hrs, 18 hrs, 24 hrs, 48 hours following the completion of the injection during the July and August. The frequency of groundwater sampling diminished to collection 1 hour following injection and follow up sampling several days to weeks later corresponding to September, October and November injections. The sampling schedule can be found in Appendix 6. Wells located in Row 1 are approximately 1.7 to 2 m from the injection well MW-501.

D.5.2 Row 2

Groundwater sampling of Row 2 commenced on day 8 following the first injection and took place on 14 days throughout the 143 day sampling period. The sampling program of multilevel wells located in Row 2 was determined based on estimated arrival times inferred from natural groundwater flow conditions at the Site. Wells situated in Row 2 are relatively 5 m downgradient of injection well MW-501.

D.5.3 Sample Storage

Samples analyzed for bromide were left stored at room temperature prior to analysis. Samples analyzed for nitrate and nitrite were either stored in the refrigerator at 4 °C if sample analysis was to occur within 48 hours or placed in the freezer until sample analysis was feasible. Frozen samples were removed from the freezer and placed in the fridge to thaw for 24 hours and well shaken prior to analysis.

Figure D.5: Adding solutes and mixing test solution.

Figure D.6: Sparging test solution with N_2 to lower $O_2 < 1$ mg/L

Figure D.7: Test solution anoxic following 1 hr N_2 sparging.

Figure D.8: Injection Test Setup

Figure D.9: Gauge used to measure flow rate and volume injected.

Figure D.10: Monitoring water levels during injection.

Appendix E

Remedial Tracer Test Injection Analysis of the Results

Injection Results

Water table mounding and recovery during injection phase in MW-401-4, MW-402-4 and MW-603 measured using the water level tape. Percent recovery (%) representative of aquifer recovery at t=150 min (86 minutes following the completion of the injection solution). "WL" denotes water level.

Table E.1: Water table mounding and recovery during injection phase in MW-401-4.

MW ID	Time (min)	WL Elevation (m AMSL)	Rise in WL (m)
MW-401-4 Screened across Unit 4 (Sand)	0	305.06	0
	5	305.20	0.13
	24	305.32	0.25
	35	305.37	0.31
	49	305.42	0.36
	66	305.49	0.43
	79	305.34	0.28
	95	305.25	0.19
	108	305.22	0.16
	128	305.15	0.09
	150	305.15	0.09
		WL at 95% Recovery (m)	0.02
		Actual % Recovery at t = 150 min	79

Table E.2: Water table mounding and recovery during injection phase in MW-402-4.

MW ID	Time (min)	WL Elevation (m AMSL)	Rise in WL (m)
MW-402-4 Screened partially across Unit 4 (Sand) and Unit 5 (Sand + Gravel)	0	305.07	0.00
	6	305.21	0.14
	14	305.26	0.19
	29	305.37	0.30
	42	305.43	0.22
	55	305.55	0.34
	77	305.43	0.22
	96	305.39	0.17
	115	305.26	0.05
	123	305.24	0.02
	150	305.21	0.00
		WL at 95% Recovery (m)	0.02
		Actual % Recovery at t = 150 min	100

Table E.3: Water table mounding and recovery during injection phase in MW-603.

MW ID	Time (min)	WL Elevation (m AMSL)	Rise in WL (m)
MW-603 Screened partially across Unit 4 (Sand) and Unit 5 (Sand + Gravel)	0	304.36	0.00
	44	304.50	0.14
	66	304.49	0.13
	92	304.43	0.06
	108	304.42	0.06
	116	304.41	0.05
	129	304.41	0.05
	152	304.40	0.04
		WL at 95% Recovery (m)	0.01
		Actual % Recovery at t = 152 min	70

Table E.4: Water table mounding and recovery during injection phase in MW-501.

MW ID	Time (min)	WL Elevation (m AMSL)	Rise in WL (m)
MW-501 Screened predominantly in Unit 4 (Sand) with partial penetration of Unit 3 (Sand + Gravel)	0	304.39	0
	98	305.40	1.01
	113	305.05	0.67
	121	304.97	0.59
	137	304.87	0.49
	146	304.82	0.44
		WL at 95% Recovery (m)	0.34
		Actual % Recovery at t = 146 min	94

Table E.5: Water table mounding and recovery during injection phase in MW-405-3.

MW ID	Time (min)	WL Elevation (m AMSL)	Rise in WL (m)
MW-405-3 Screened fully in Unit 4 (Sand)	0	304.07	0
	10	304.07	0
	27	304.07	0
	63	304.07	0
	89	304.07	0
	147	304.07	0
		WL at 95% Recovery (m)	NA
		Actual % Recovery at t = 146 min	NA

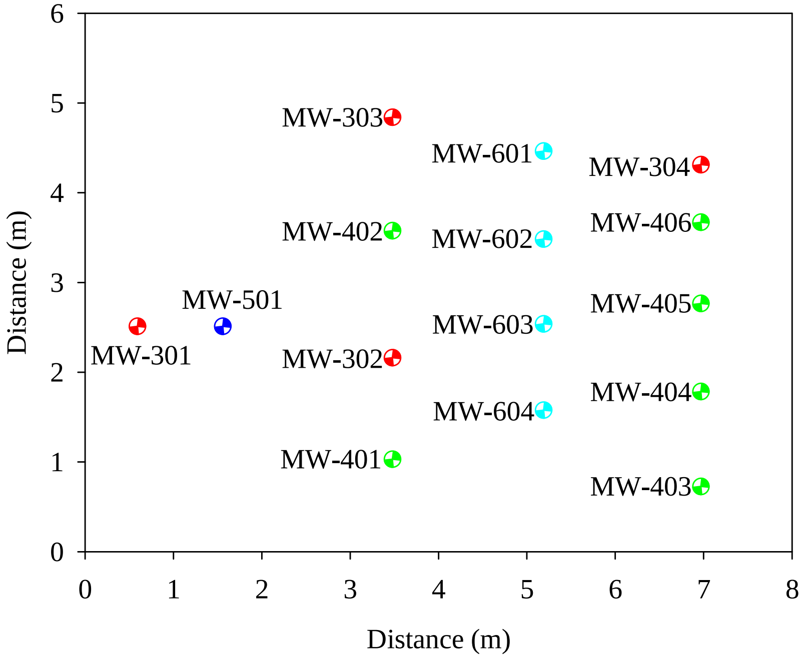
Table E.6: Description of stratigraphic units corresponding to monitoring points.

Stratigraphic Unit	Description	Monitoring Well (MW) Port
Unit 2	Sand	302-5, 403-1, 403-2
Unit 3	Sand + Gravel (till)	302-6, 401-1, 401-2, 401-3, 402-1, 402-2, 402-3, 402-4, 403-3, 406-4, 406-5
Unit 4	Sand	302-7, 302-8, 302-9, 401-4, 401-5, 401-6, 401-7, 401-8, 401-9, 402-5, 402-6, 402-7, 402-8, 402-9, 403-4, 403-5, 403-6, 403-7, 405-1, 405-2, 405-3, 405-4, 405-6, 405-7, 406-6, 406-7, 601, 602, 603*, 604
Unit 5	Sand + Gravel (till)	403-8, 403-9, 405-8, 405-9, 406-8, 406-9

Notes:

* well screened partially screened in units 3 and 4.

Borehole logging of BH-404/MW-404 was not completed due to boulder encountered during drilling



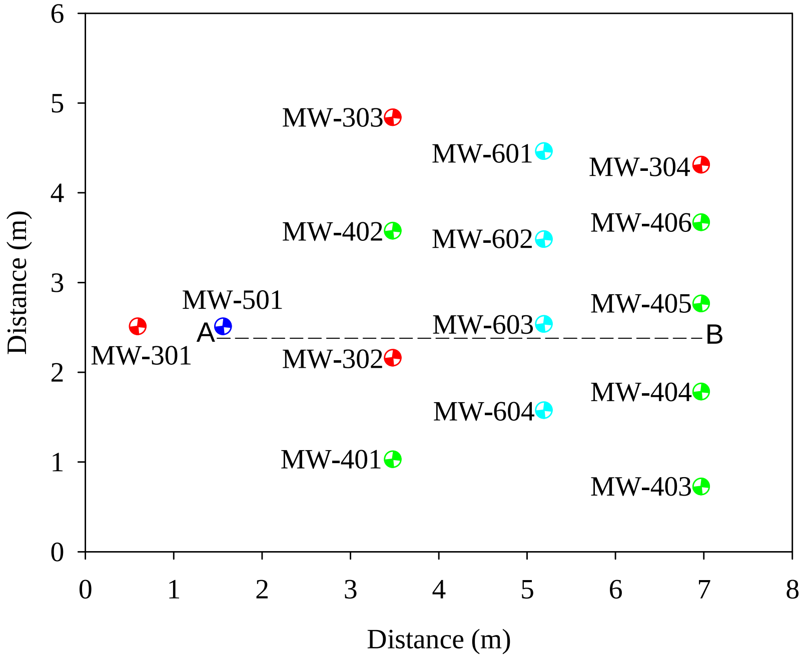


Figure E.1: Plan view of in situ remediation injection well (MW-501) and monitoring network (MW series 300, 400 and 600). Please note that 600 series wells were only available for the evaluation of the injected remedial slug from October 2009 onwards, as they were installed following several injections.

Table E.7: Transmissivity values of each stratigraphic unit estimated from aquifer parameters.

Stratigraphic Unit	Approximate Thickness, b (m)	Estimated K (m/s)	Transmissivity (m^2/s)
Unit 2	1	$9.8\text{x}10^{-5}$	$1\text{x}10^{-4}$
Unit 3	1.5	$6.9\text{x}10^{-5}$	$1\text{x}10^{-4}$
Unit 4	2.5	$3.1\text{x}10^{-5}$	$8\text{x}10^{-5}$

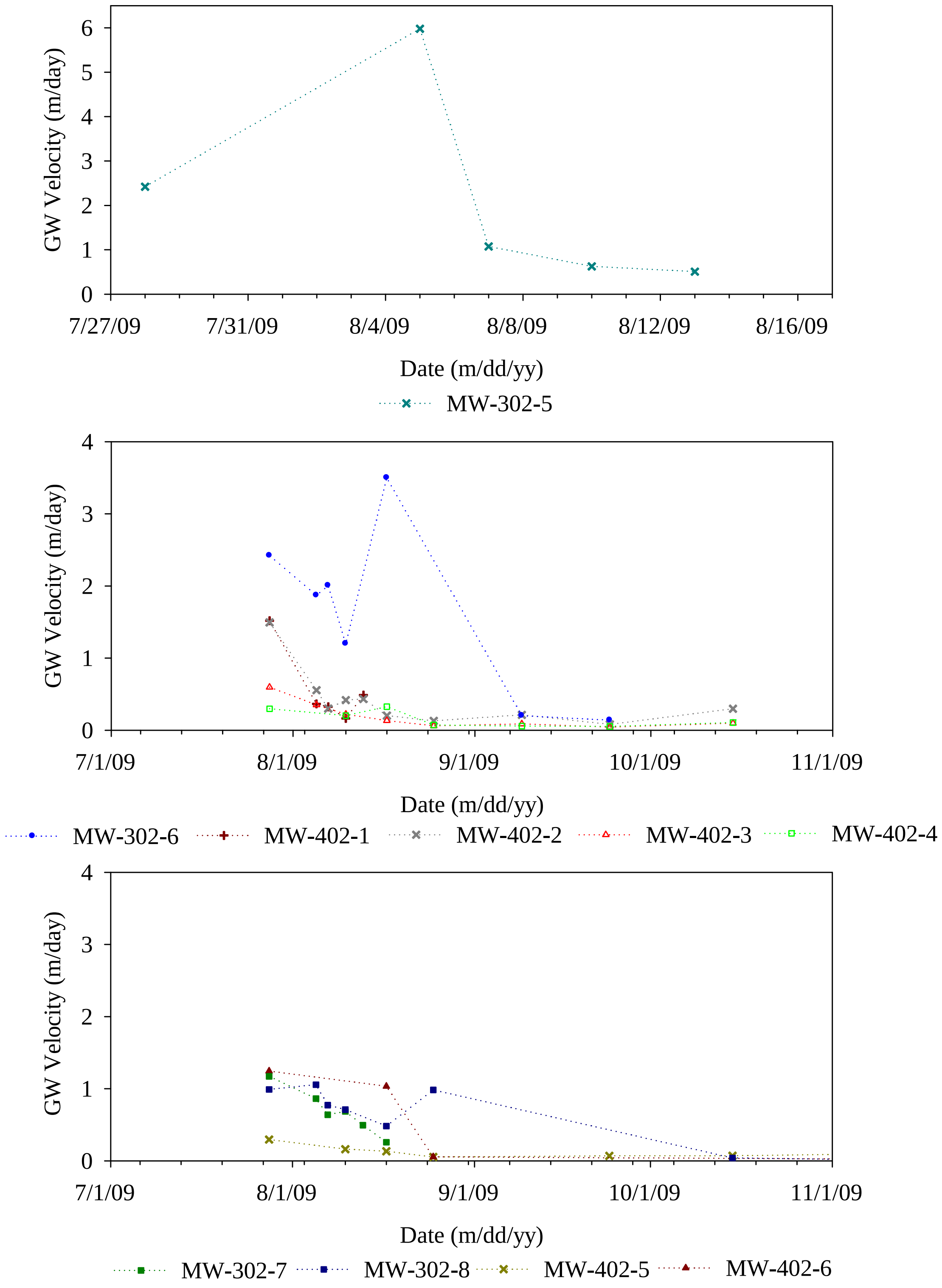


Figure E.2: Declining average linear groundwater velocities over time throughout the course of injections in Unit 2, (top) Unit 3(middle) and Unit 4 (bottom).

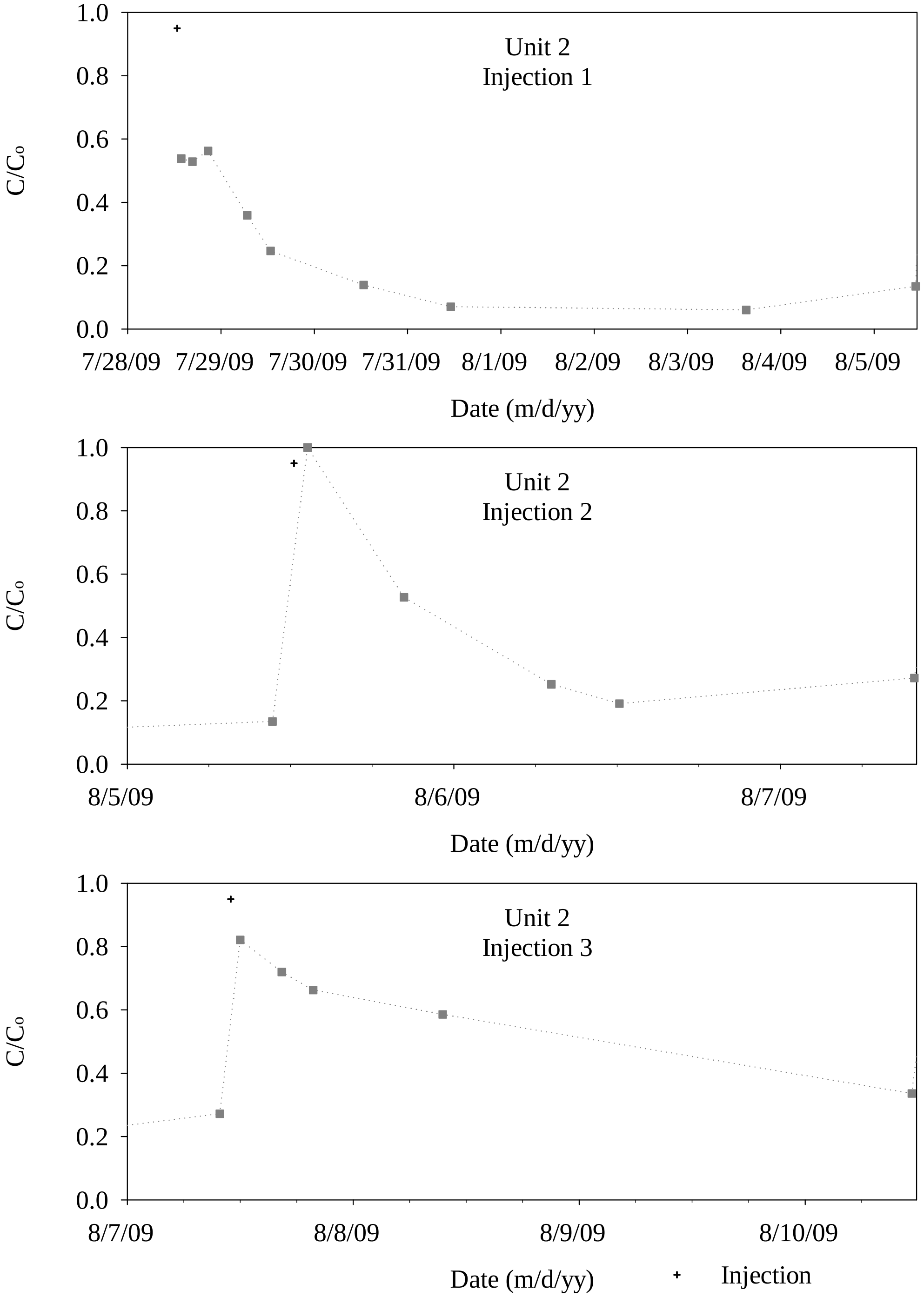


Figure E.3: Tracer breakthrough curves at Row 1 following Injections 1, 2 and 3 at multilevel well MW-302 port 5 screened within Unit 2 comprised of sandy aquifer materials.

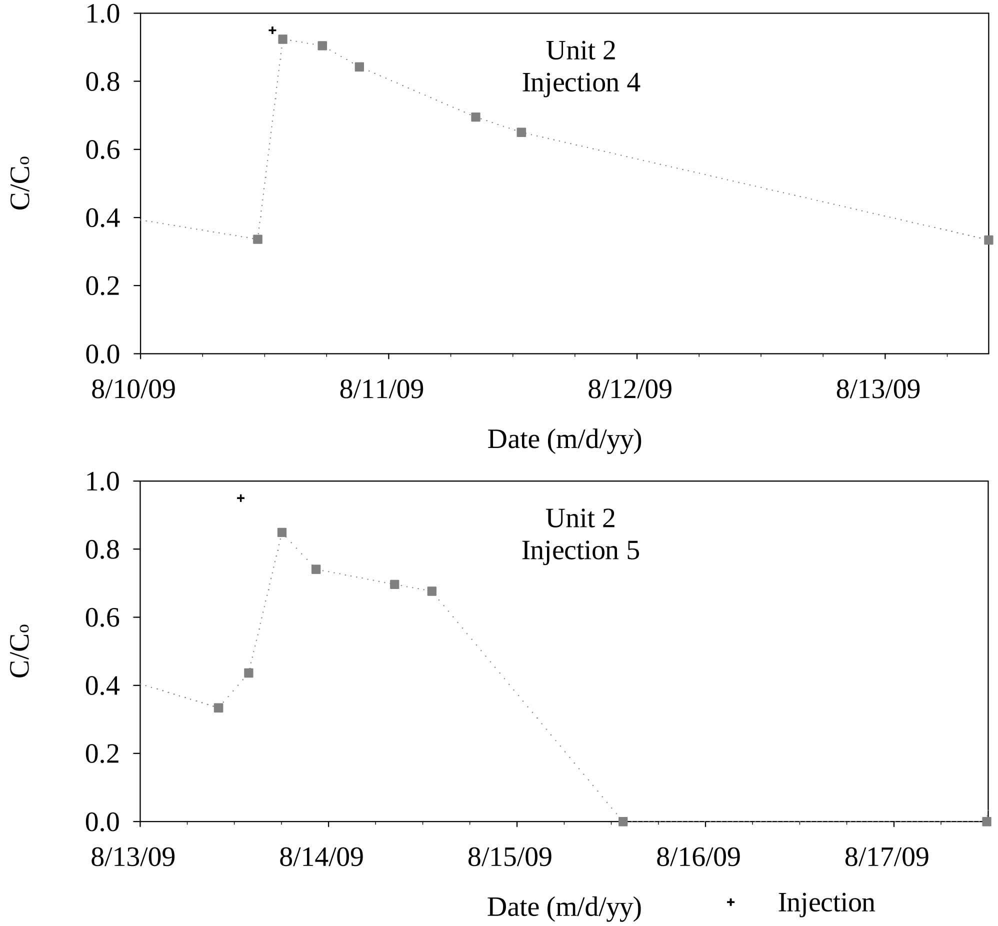


Figure E.3: Tracer breakthrough curves at Row 1 following Injections 4 and 5 at multilevel well MW-302 port 5 screened within Unit 2 comprised of sandy aquifer materials.

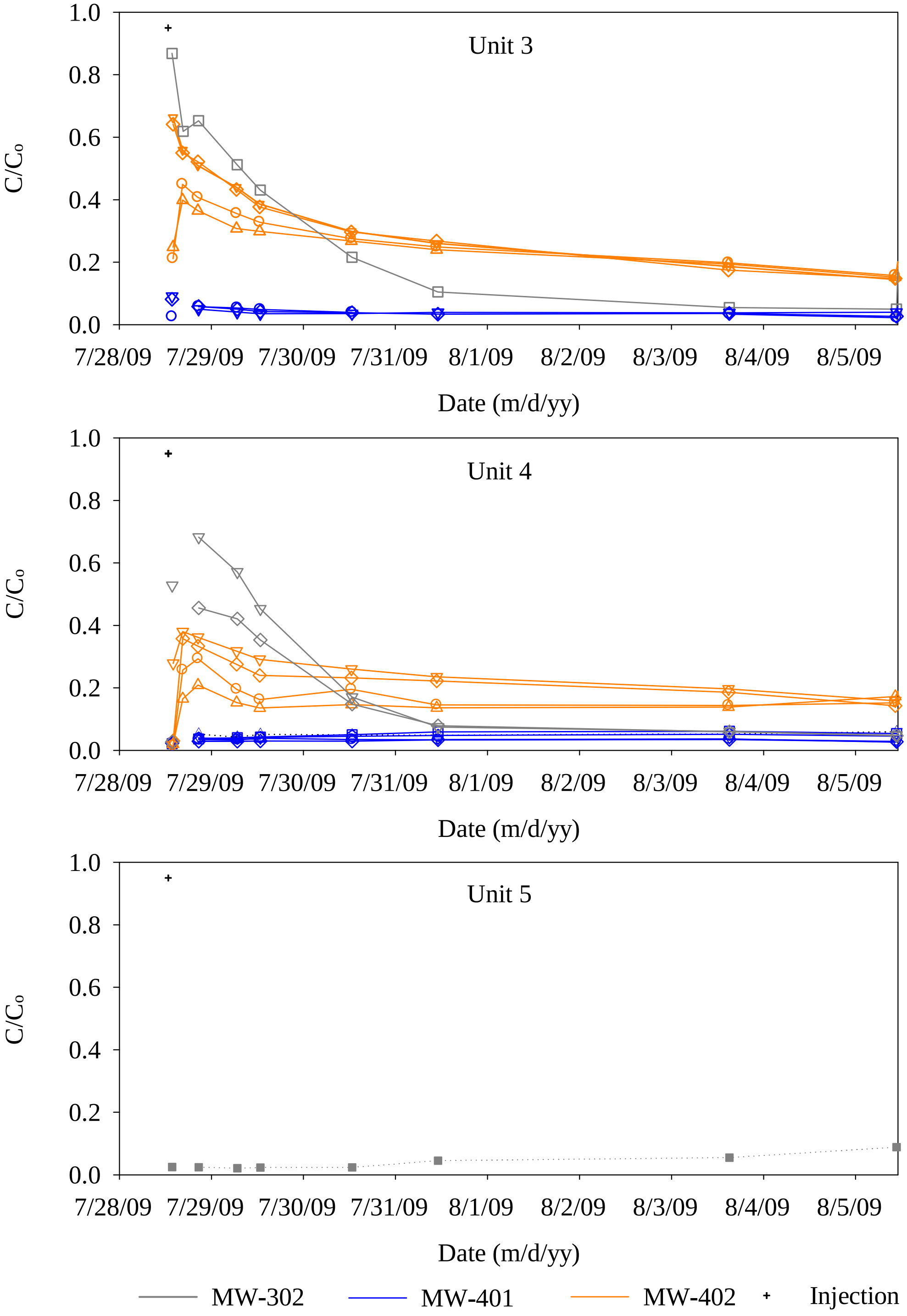


Figure E.4: Tracer breakthrough curves at Row 1 following Injection 1 at multilevel wells MW-302, MW-401 and MW-402.

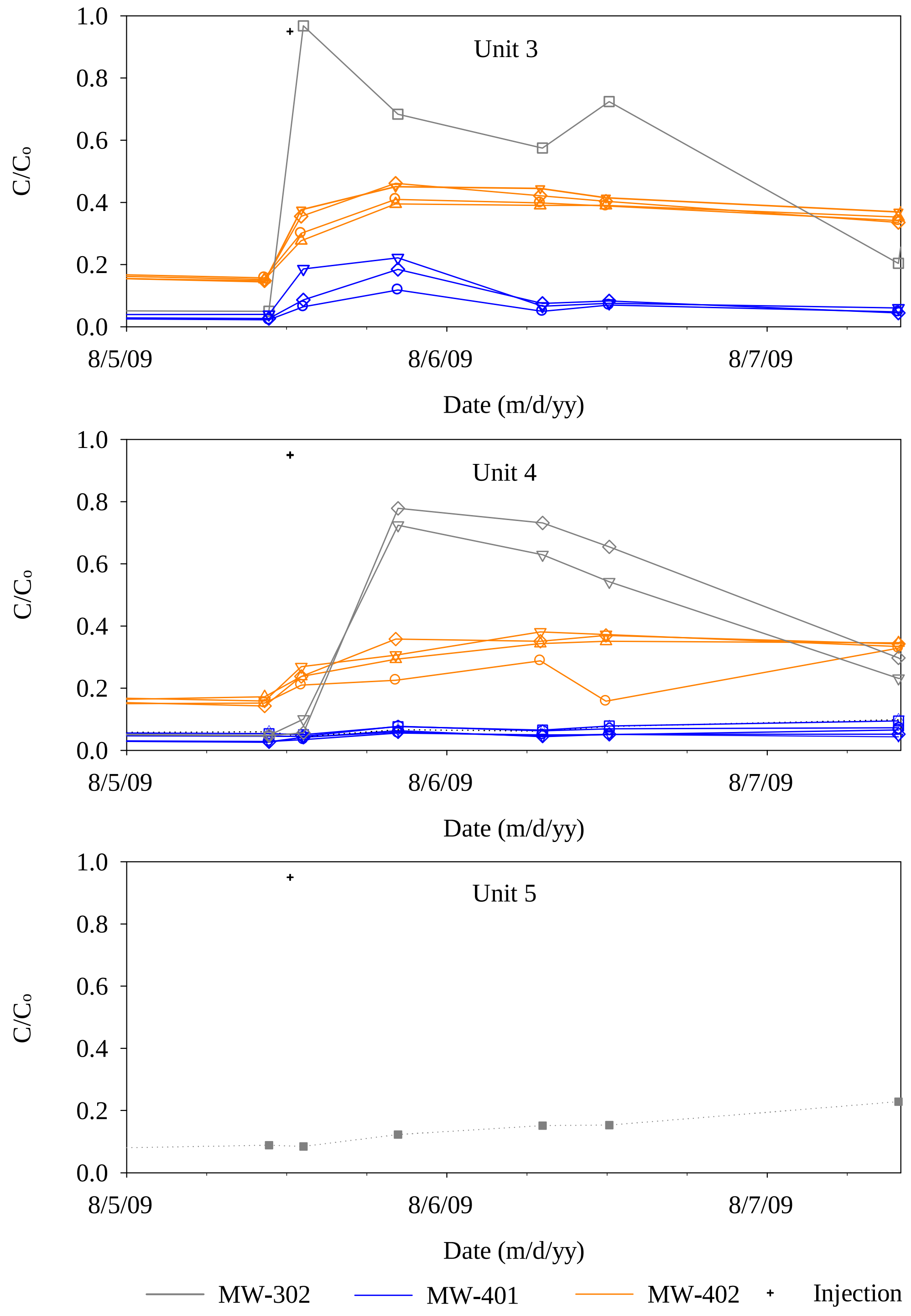


Figure E.5: Tracer breakthrough curves at Row 1 following Injection 2 at multilevel wells MW-302, MW-401 and MW-402.

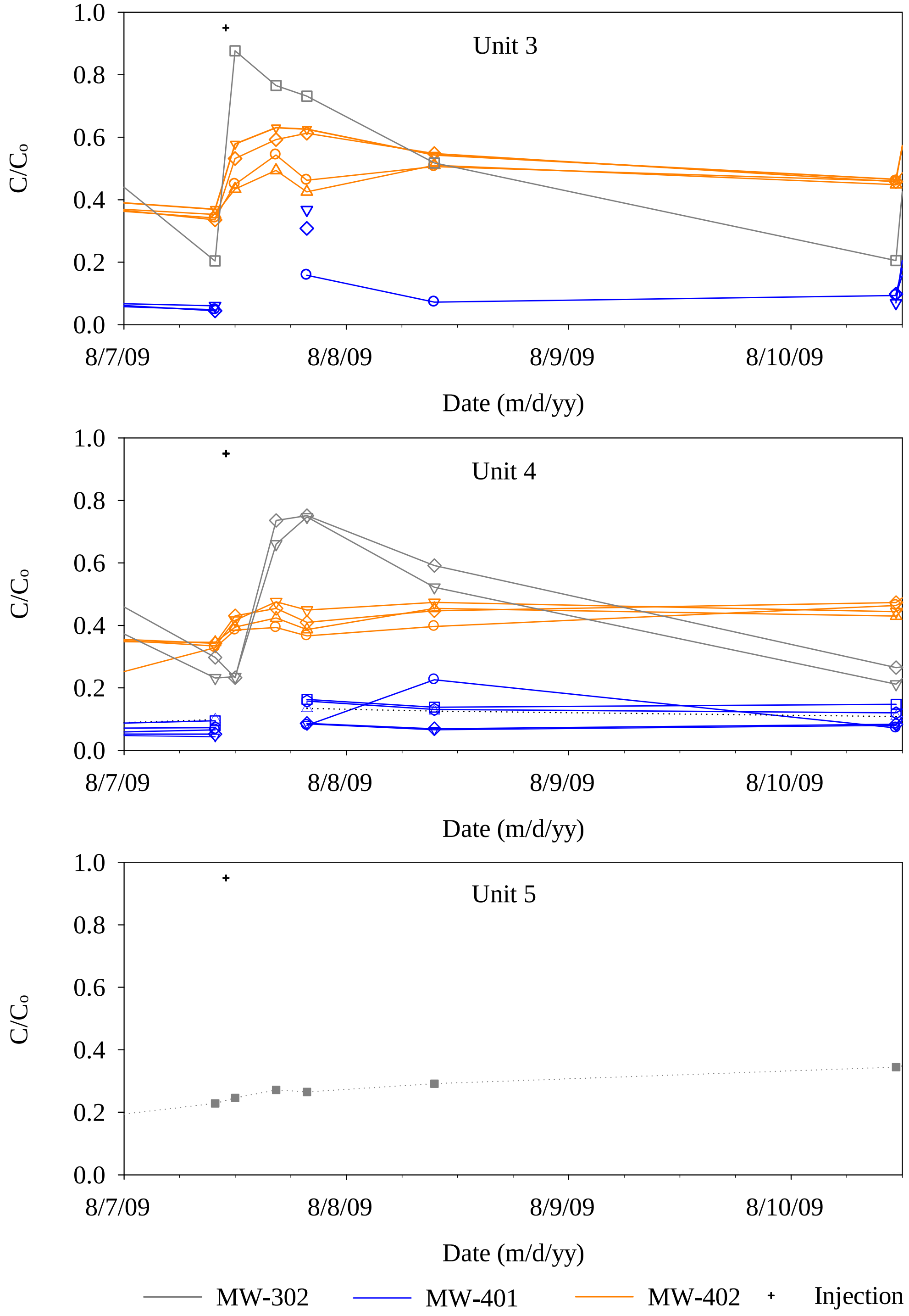


Figure E.6: Tracer breakthrough curves at Row 1 following Injection 3 at multilevel wells MW-302, MW-401 and MW-402.

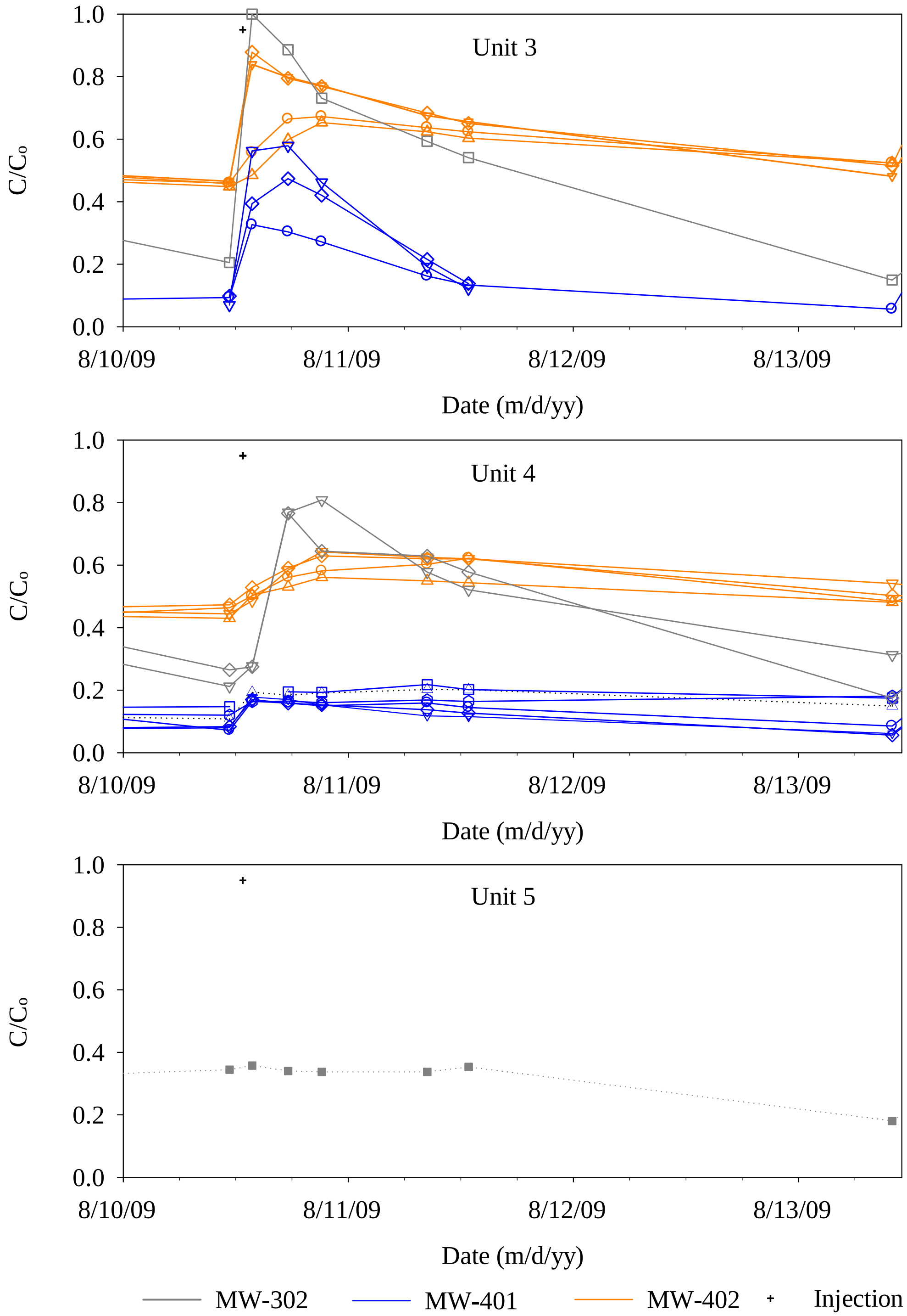


Figure E.7: Tracer breakthrough curves at Row 1 following Injection 4 at multilevel wells MW-302, MW-401 and MW-402.

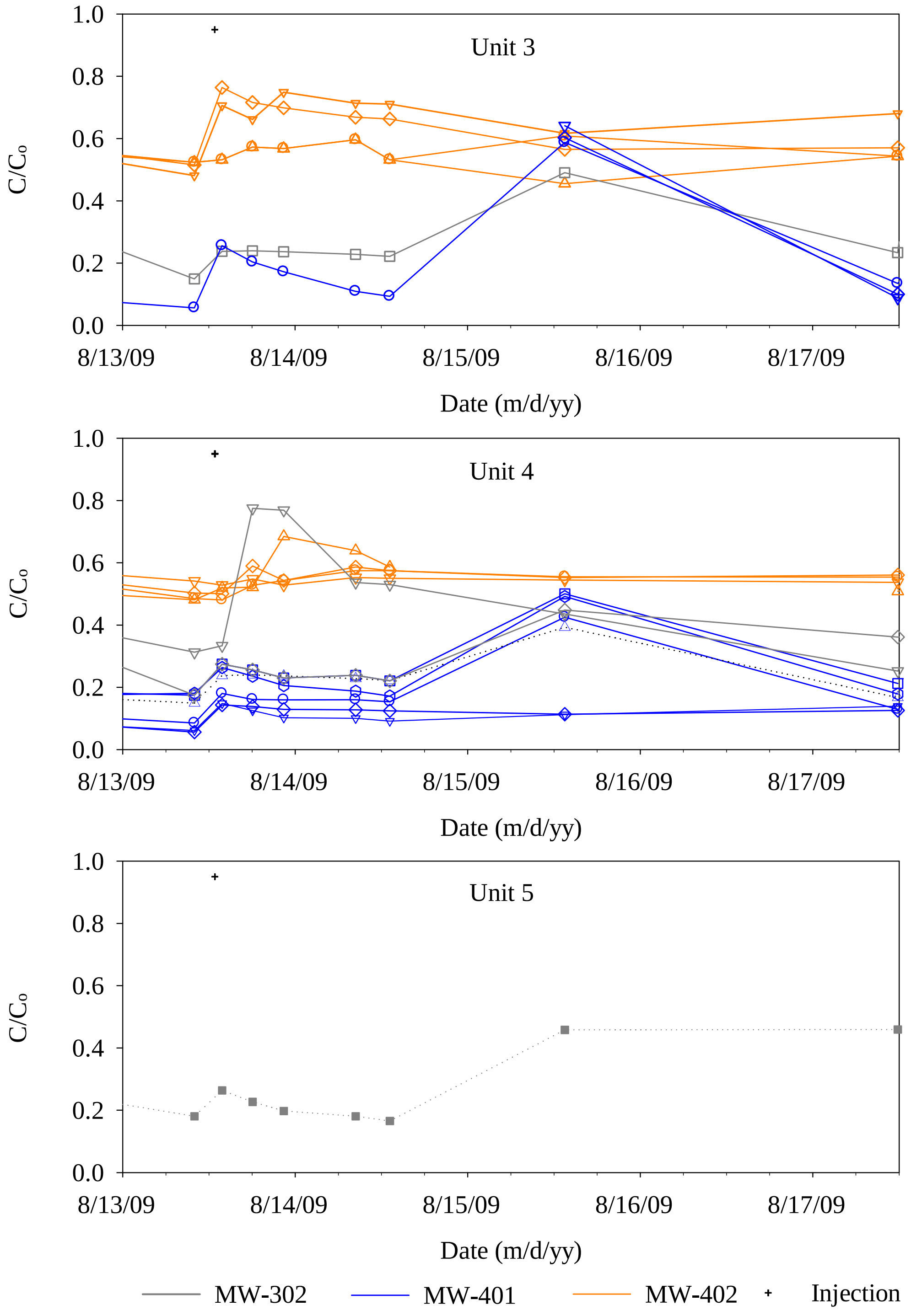


Figure E.8: Tracer breakthrough curves at Row 1 following Injection 5 at multilevel wells MW-302, MW-401 and MW-402.

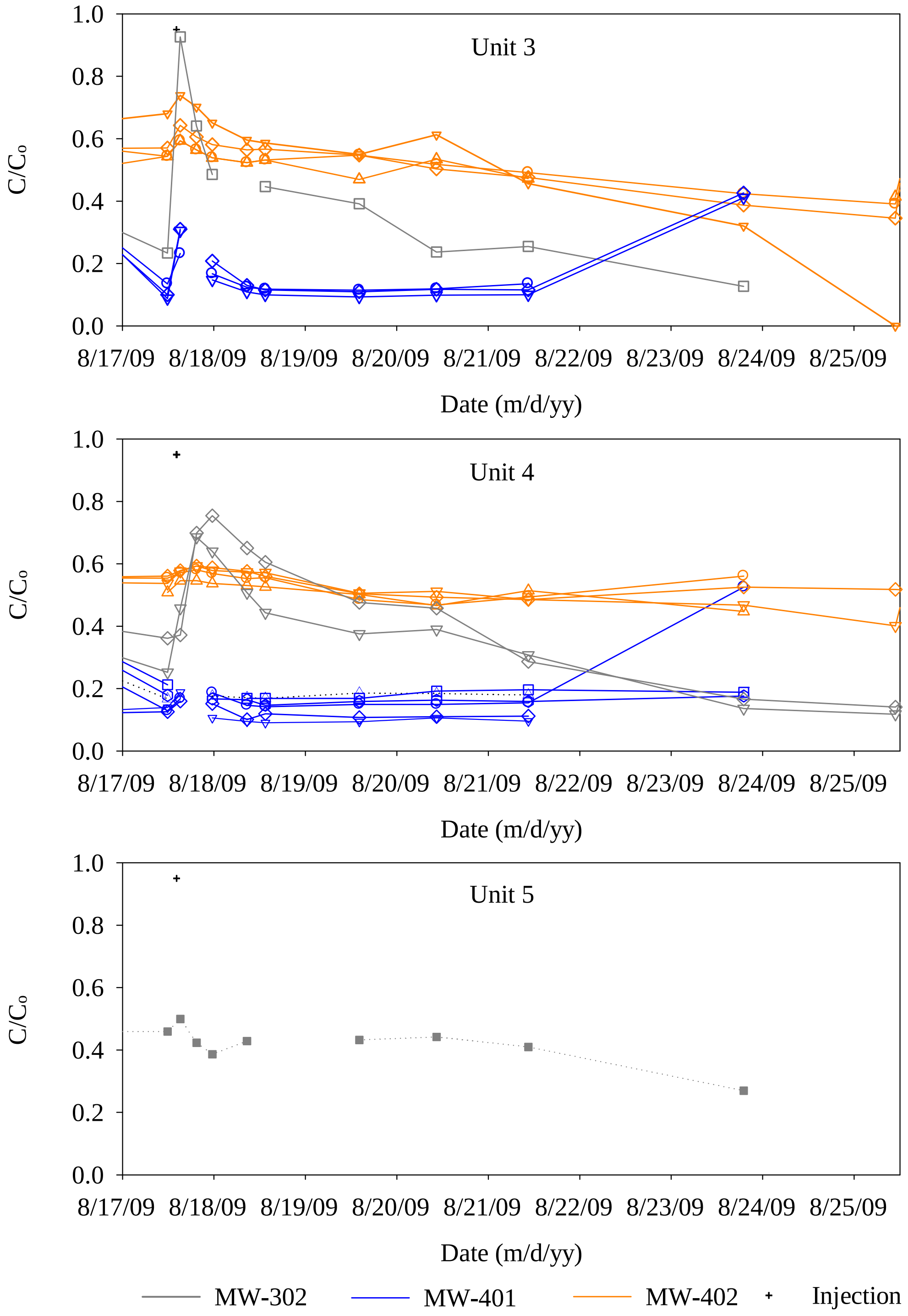


Figure E.9: Tracer breakthrough curves at Row 1 following Injection 6 at multilevel wells MW-302, MW-401 and MW-402.

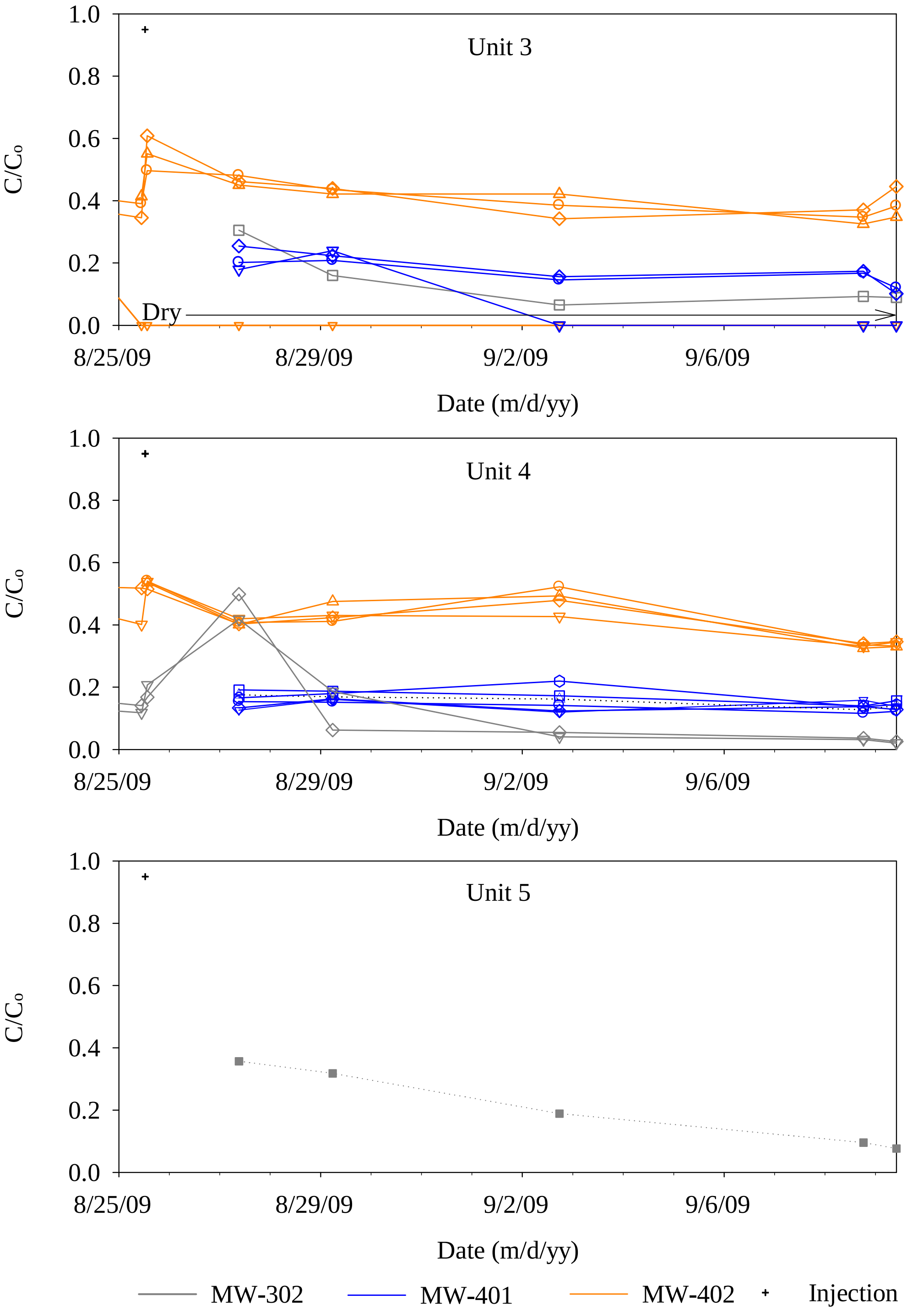


Figure E.10: Tracer breakthrough curves at Row 1 following Injection 7 at multilevel wells MW-302, MW-401 and MW-402. Multilevel well sampling points dry in MW-402 (1) at time of injection. MW-401 (1) dry from September 9, 2009 and onwards.

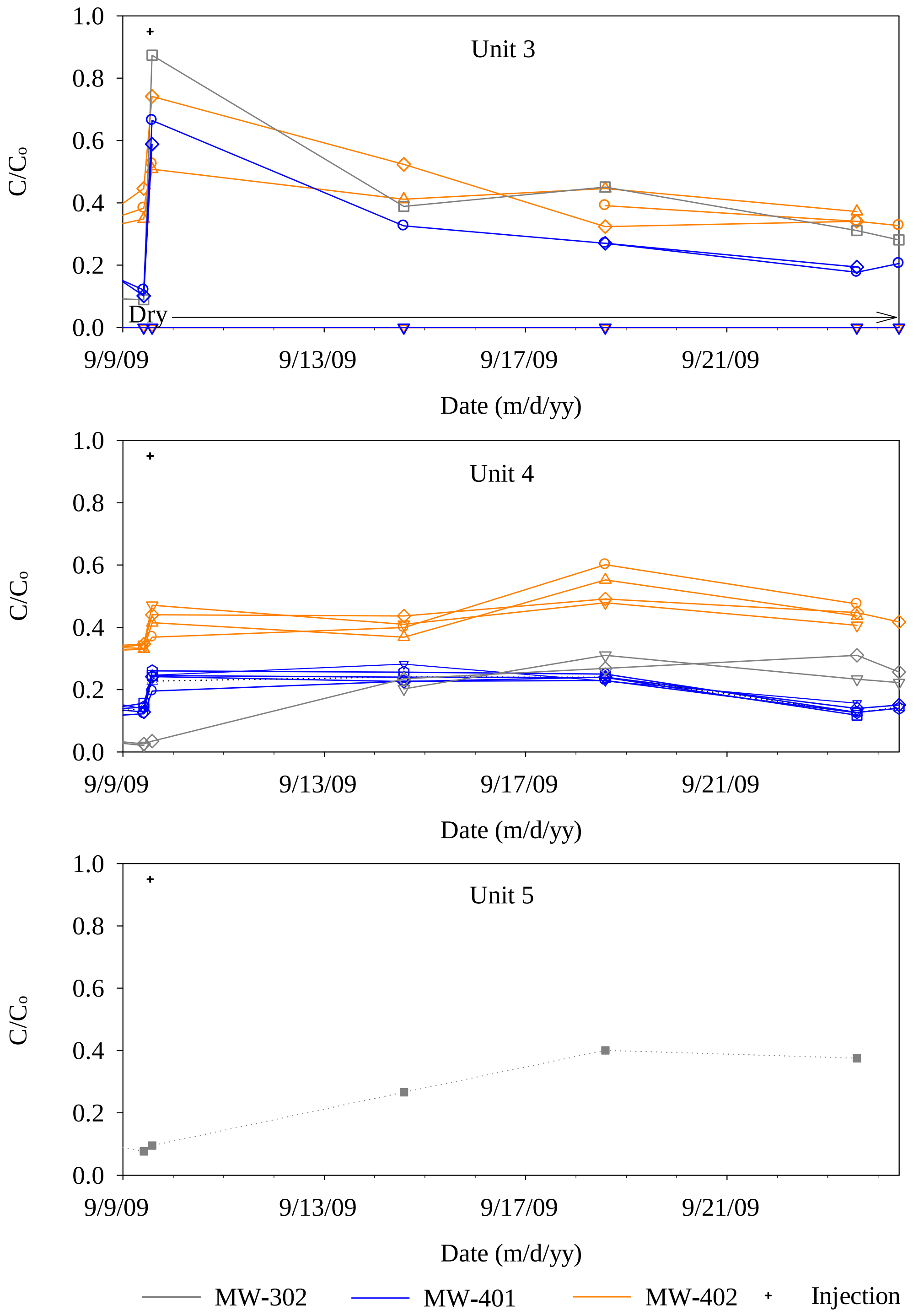


Figure E.11: Tracer breakthrough curves at Row 1 following Injection 8 at multilevel wells MW-302, MW-401 and MW-402. Multilevel well sampling points dry in MW-401 (1) and MW-402 (1) at time of injection.

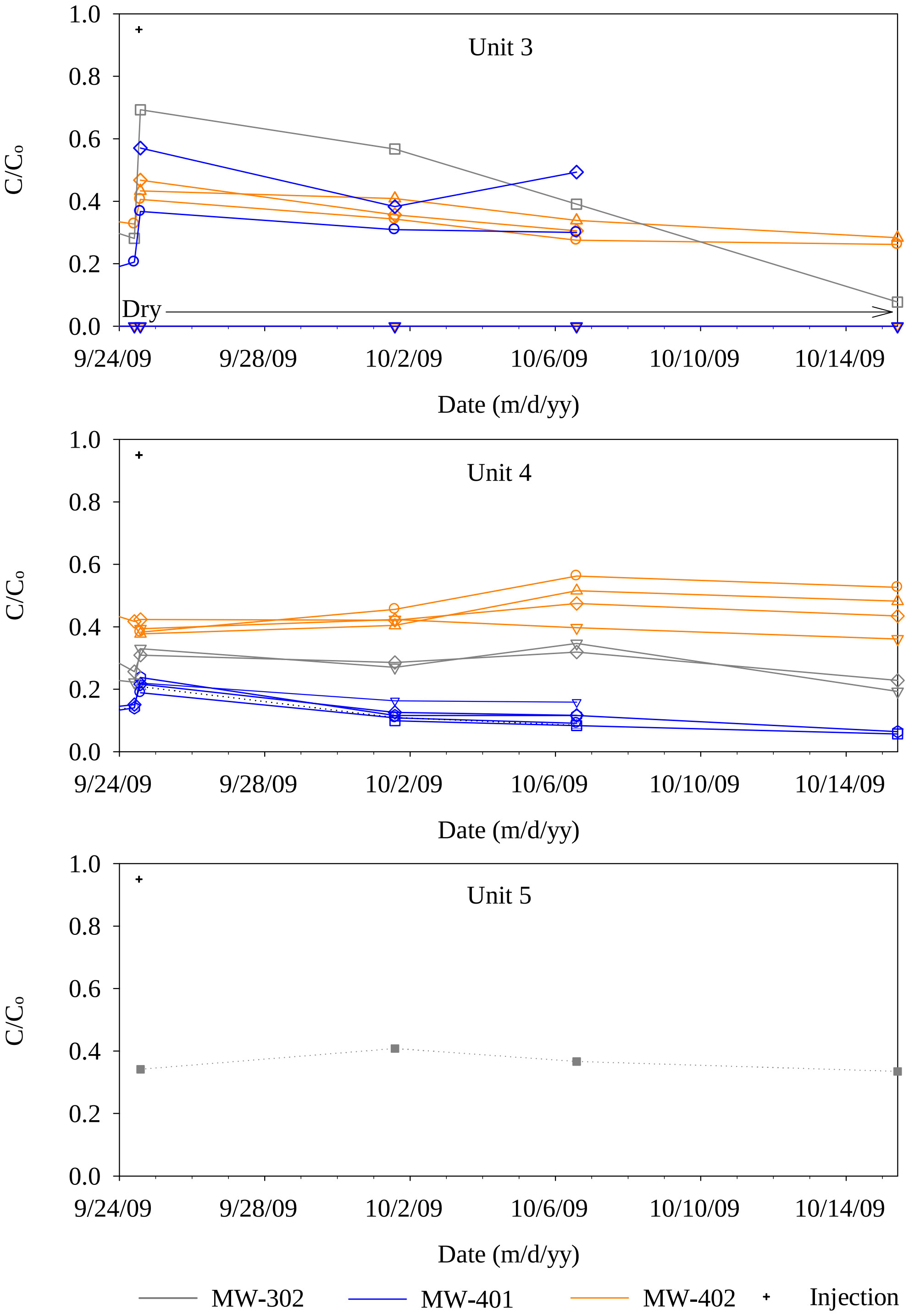


Figure E.12: Tracer breakthrough curves at Row 1 following Injection 9 at multilevel wells MW-302, MW-401 and MW-402. Multilevel well sampling points dry in MW-401 (1) and MW-402 (1) at time of injection.

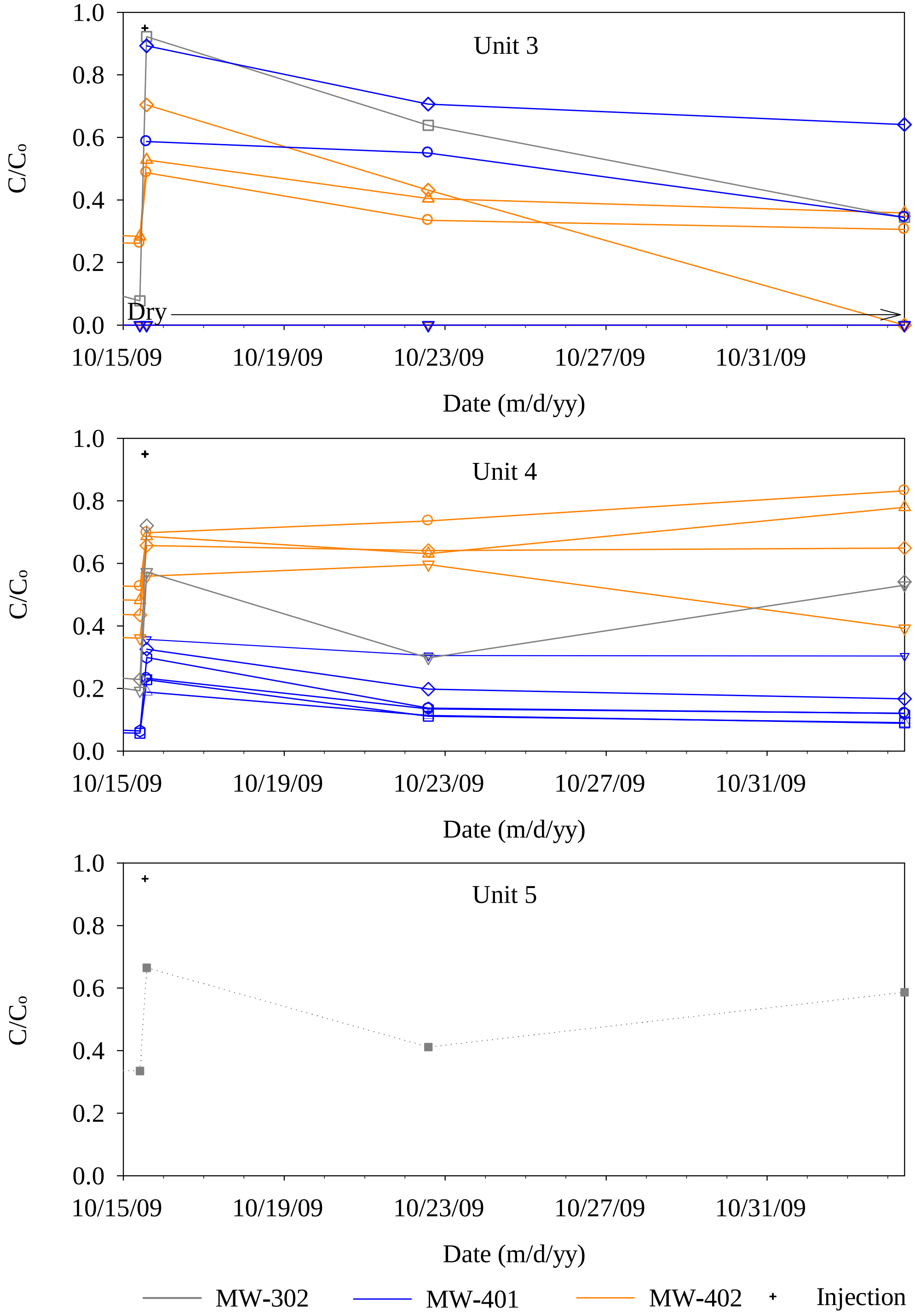


Figure E.13: Tracer breakthrough curves at Row 1 following Injection 10 at multilevel wells MW-302, MW-401 and MW-402. Multilevel well sampling points dry in MW-401 (1) and MW-402 (1) at time of injection.

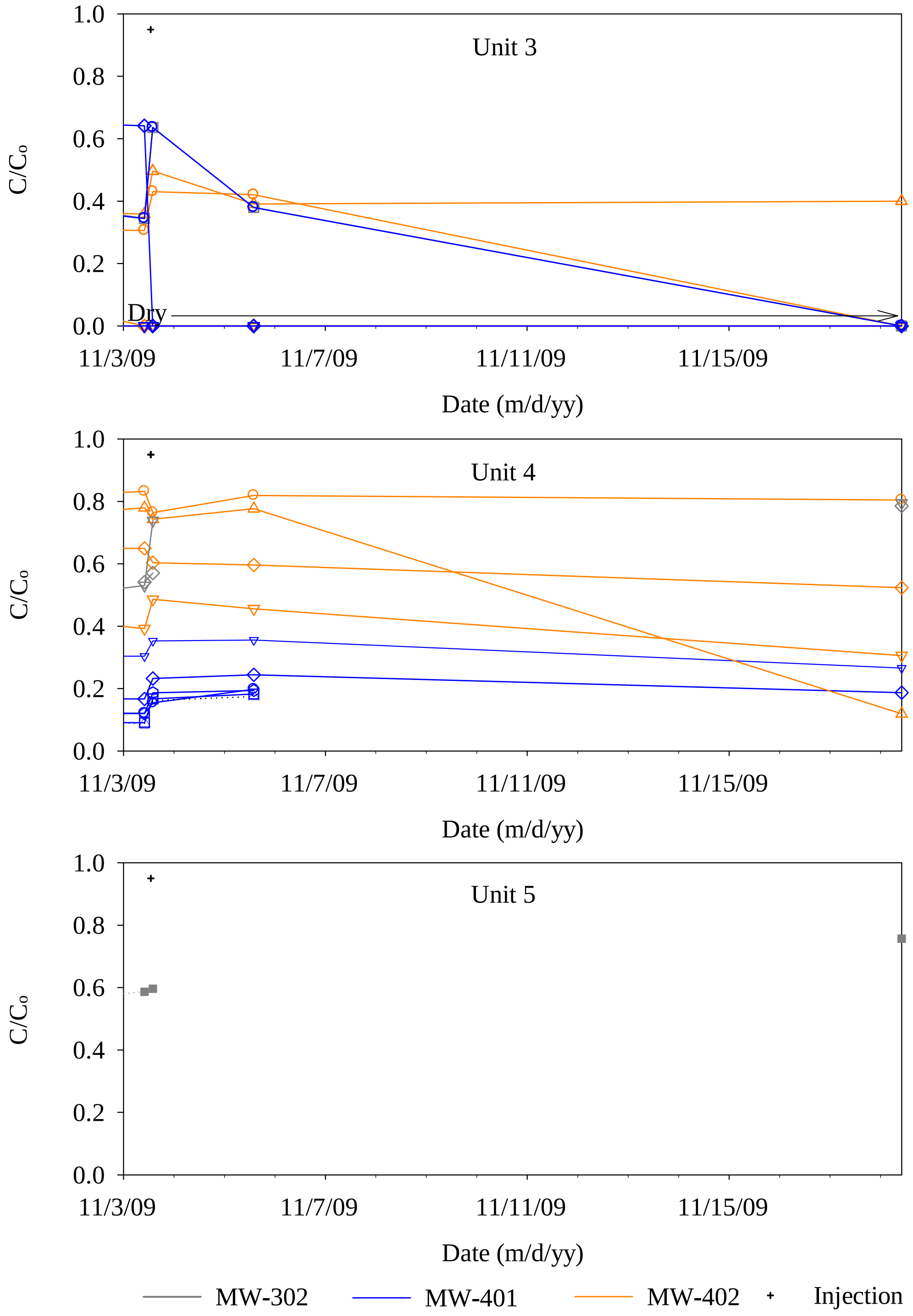


Figure E.14: Tracer breakthrough curves at Row 1 following Injection 11 at multilevel wells MW-302, MW-401 and MW-402. Multilevel well sampling points dry in MW-302 (6), MW-401 (1 & 2) and MW-402 (1 & 2) at time of injection.

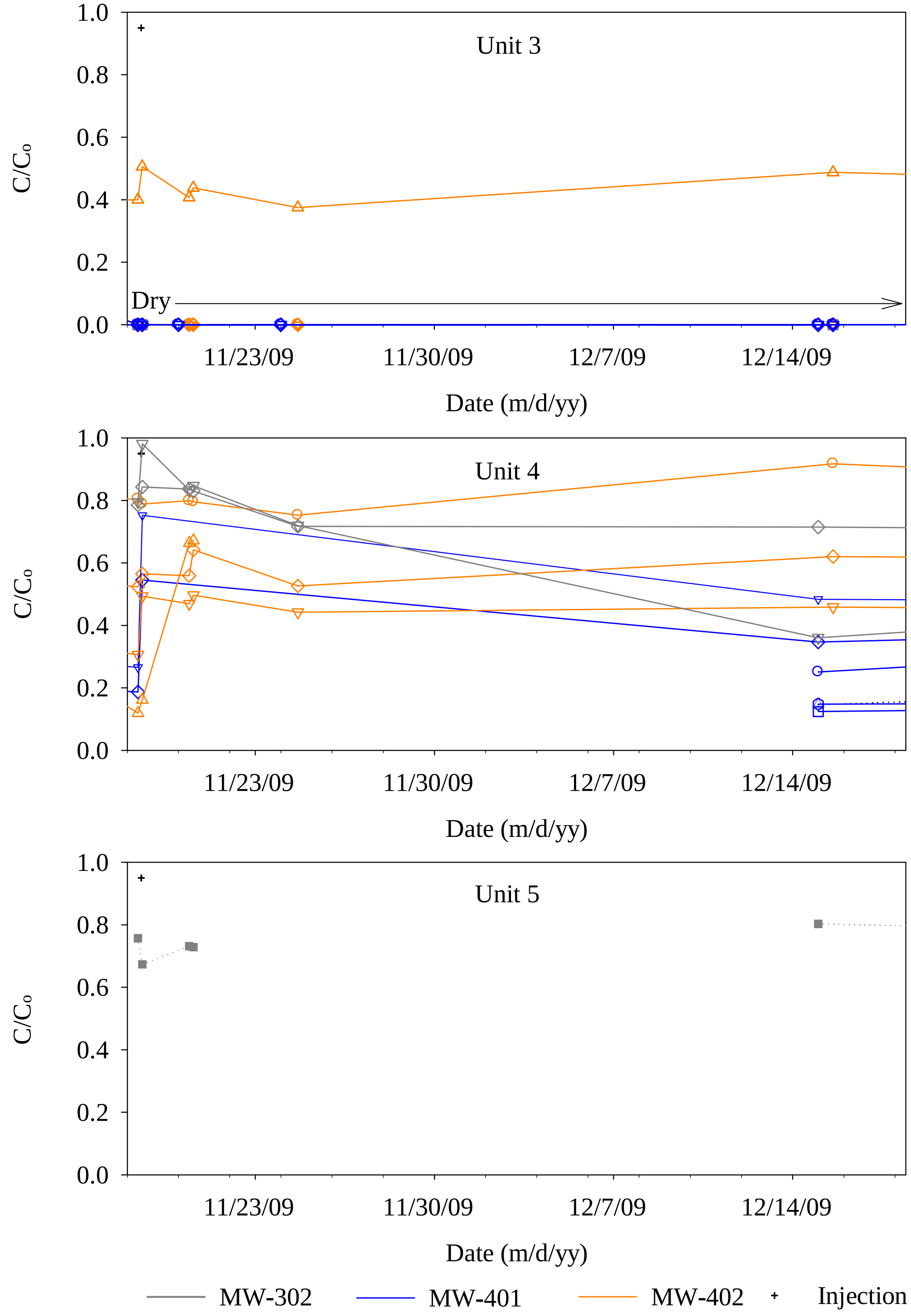


Figure E.15: Tracer breakthrough curves at Row 1 following Injection 12 at multilevel wells MW-302, MW-401 and MW-402. Multilevel well sampling points dry in MW-302 (6), MW-401 (1, 2 & 3) and MW-402 (1, 2, 3) at time of injection.

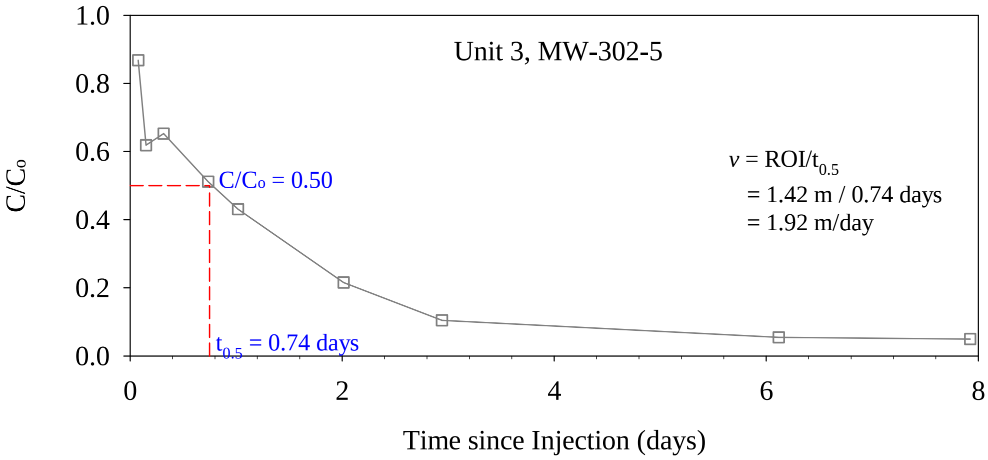


Figure E.16: Graphical determination of the time where $C/C_o = 0.5$, $t_{0.5}$used for calculating average groundwater velocity within specific aquifer units, corresponding to single multilevel well point data.

Aquifer Formation	Row 1Multilevel Well		
	MW-302	MW-401	MW-402
Unit 2	0.27	-	-
Unit 3	0.16	-	0.40
Unit 4	0.28	0.12	0.44
Unit 5	0.34	0.12	-

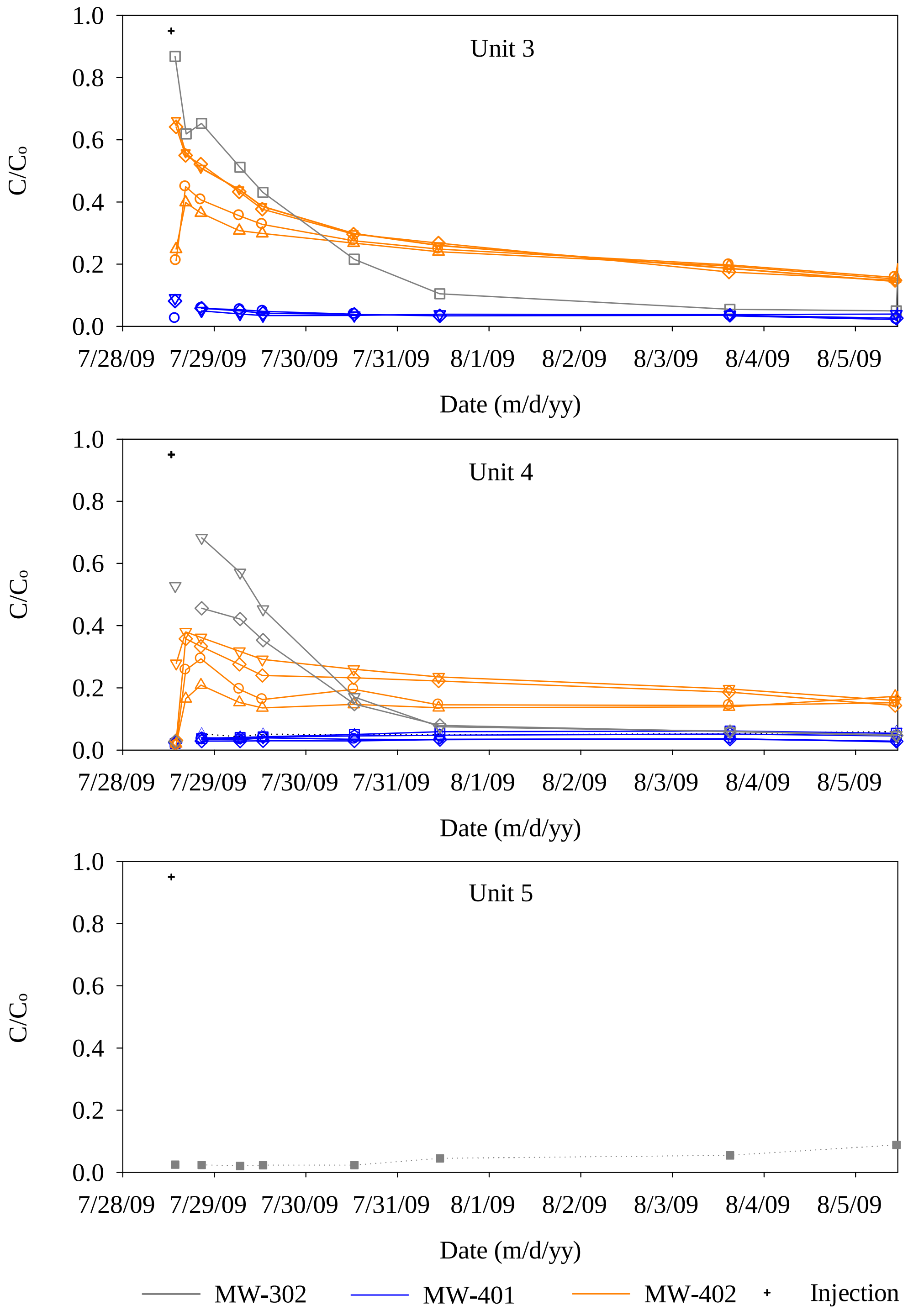


Figure E.16: Tracer breakthrough curves at Row 1 following Injection 1 at multilevel wells MW-302, MW-401 and MW-402.

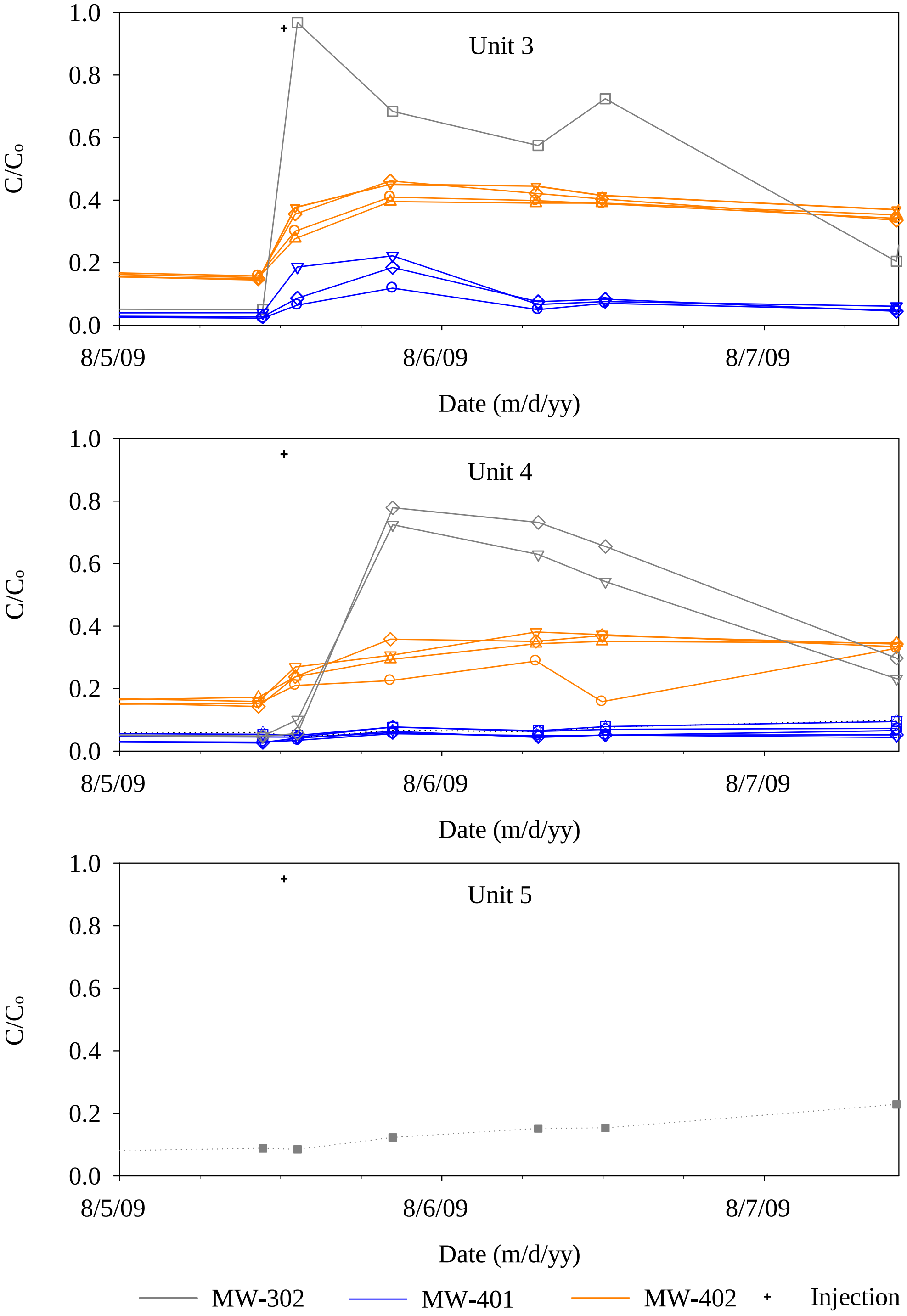


Figure E.17: Tracer breakthrough curves at Row 1 following Injection 2 at multilevel wells MW-302, MW-401 and MW-402.

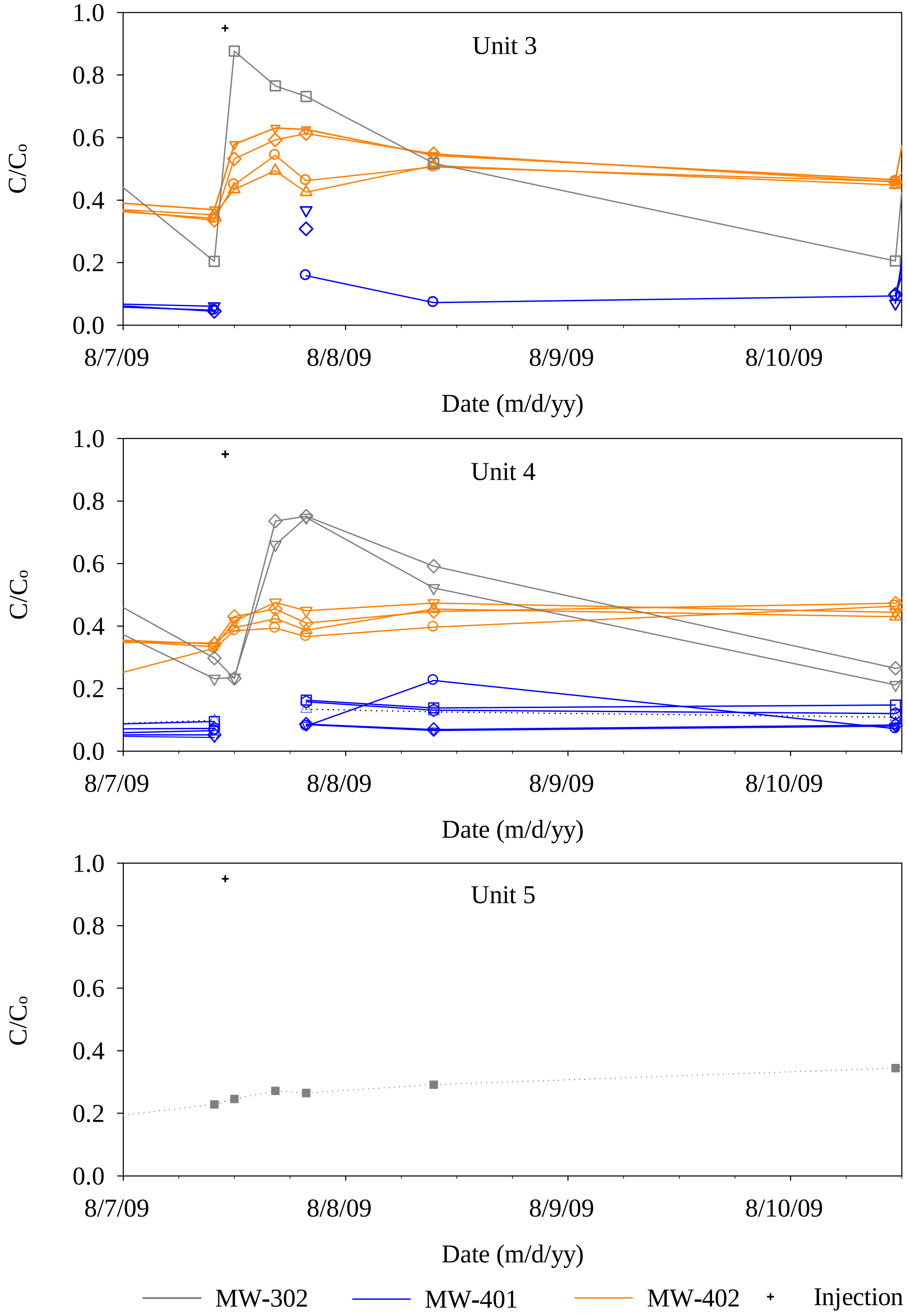


Figure E.18: Tracer breakthrough curves at Row 1 following Injection 3 at multilevel wells MW-302, MW-401 and MW-402.

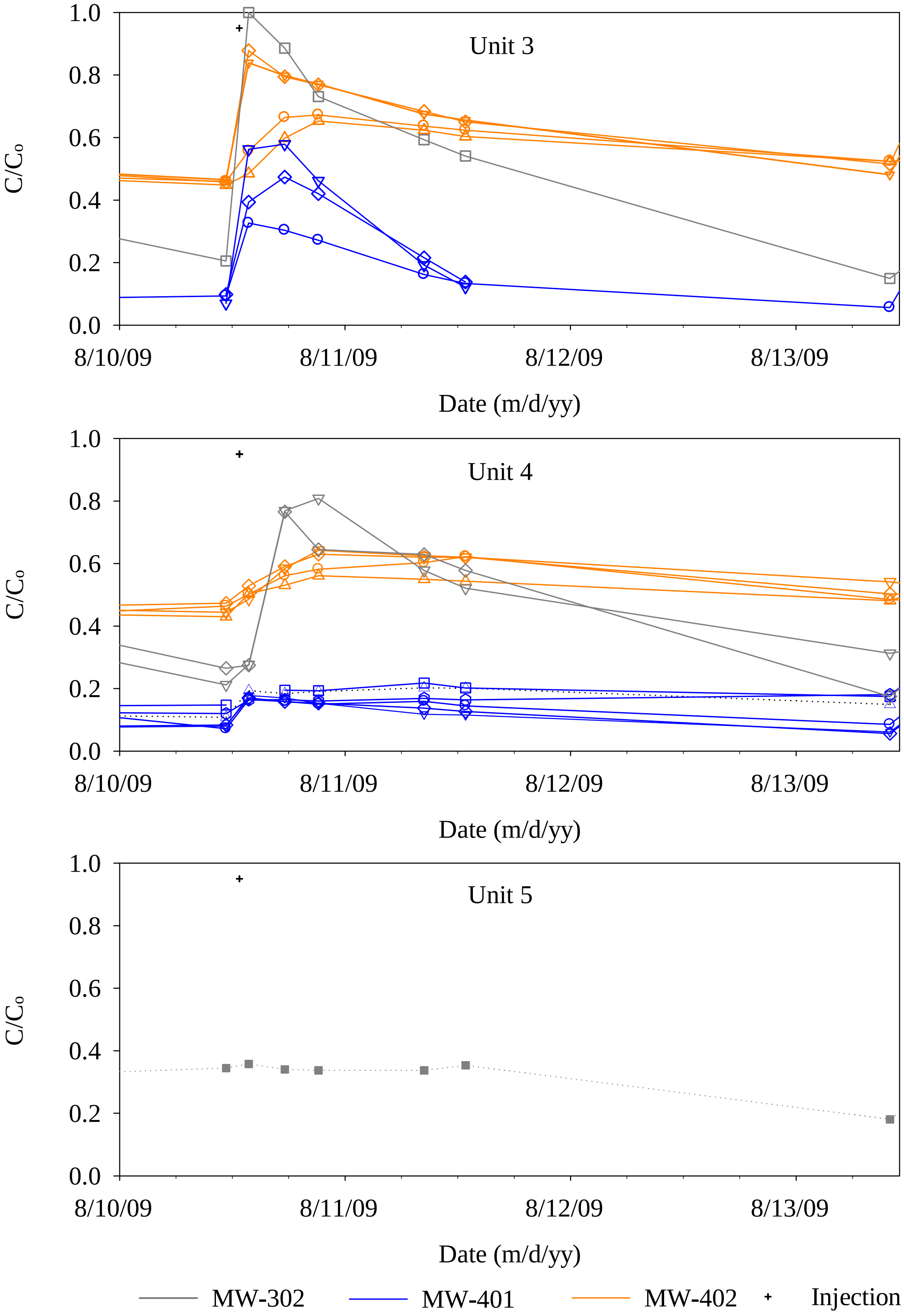


Figure E.19: Tracer breakthrough curves at Row 1 following Injection 4 at multilevel wells MW-302, MW-401 and MW-402.

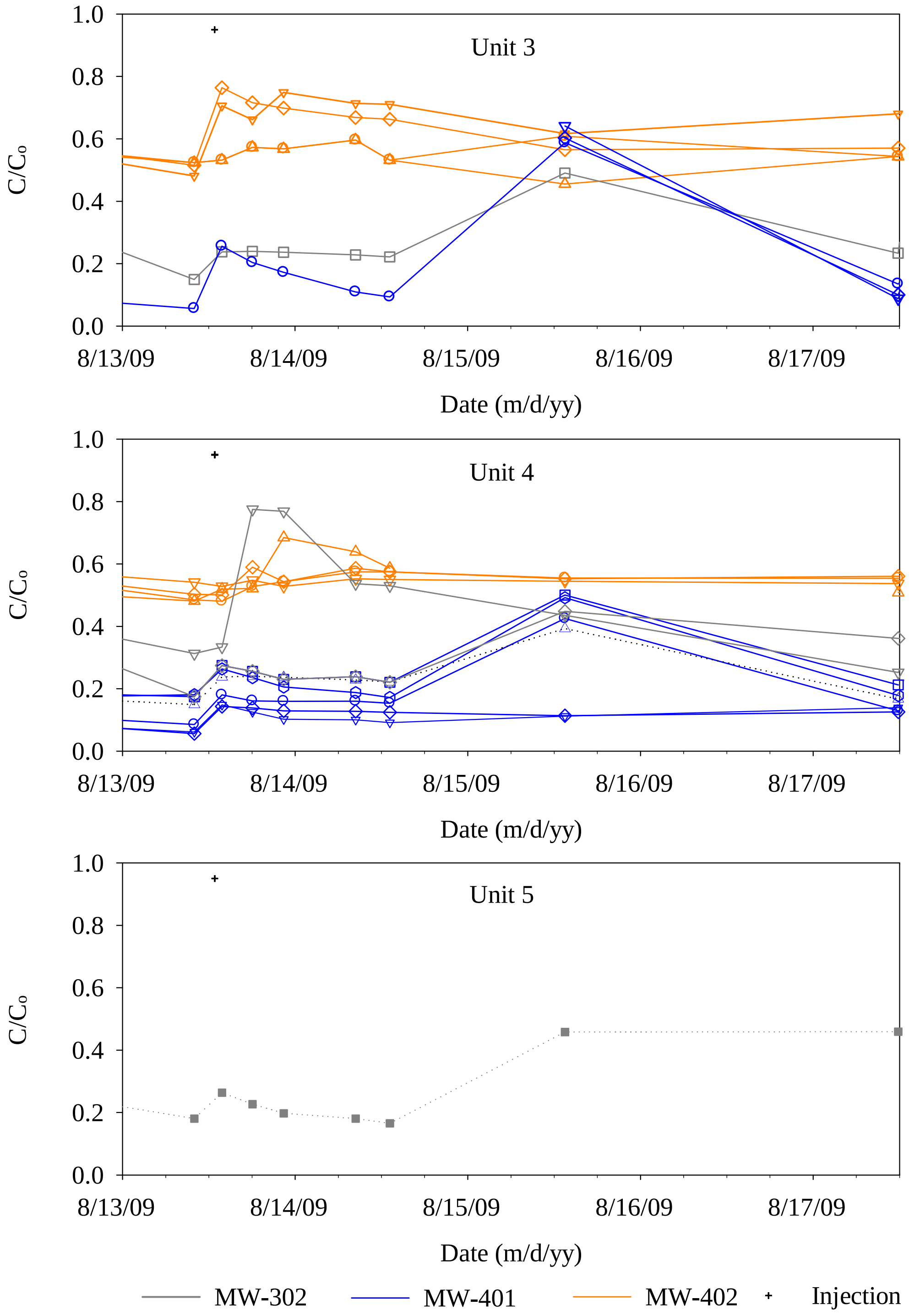


Figure E.20: Tracer breakthrough curves at Row 1 following Injection 5 at multilevel wells MW-302, MW-401 and MW-402.

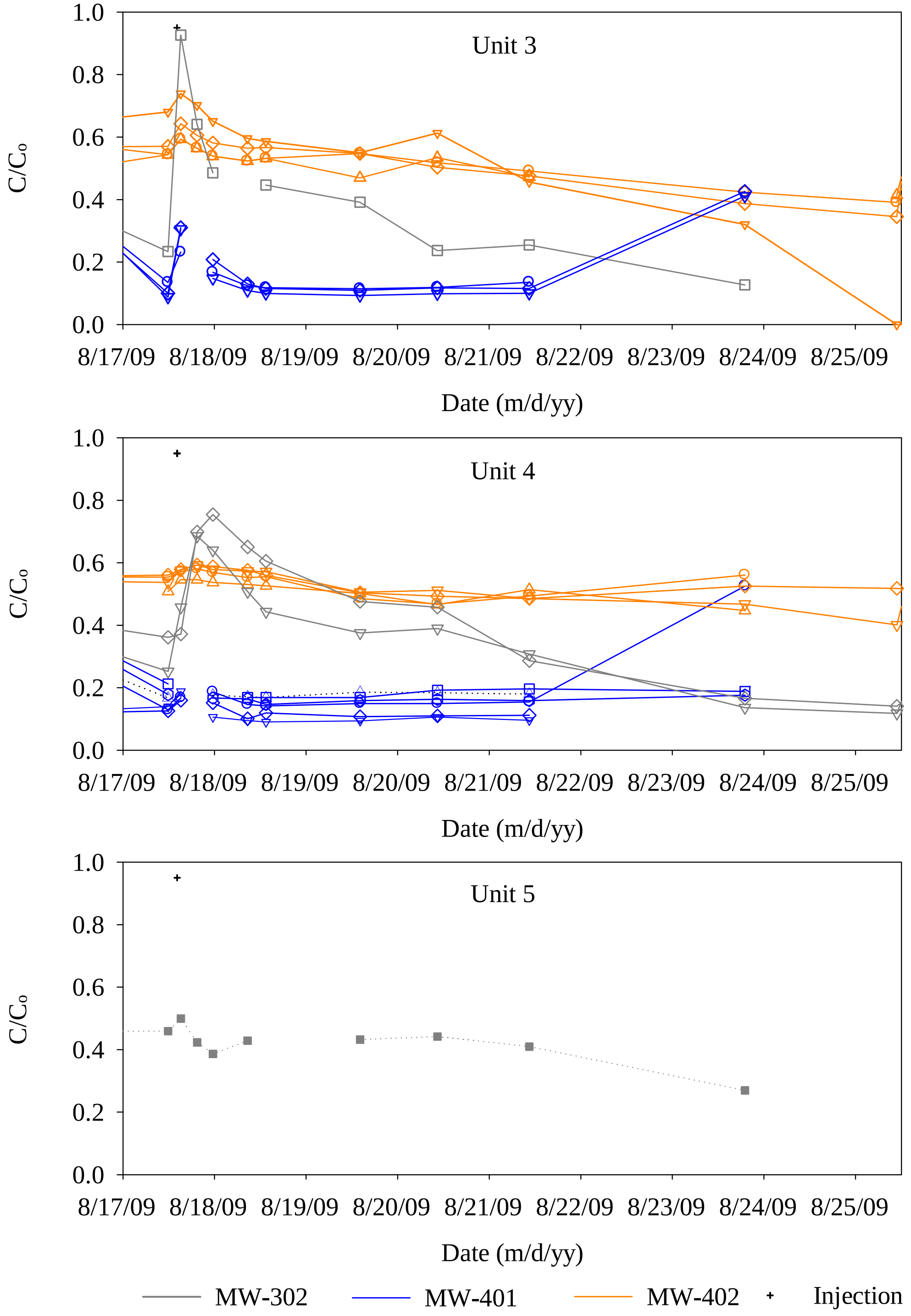


Figure E.21: Tracer breakthrough curves at Row 1 following Injection 6 at multilevel wells MW-302, MW-401 and MW-402.

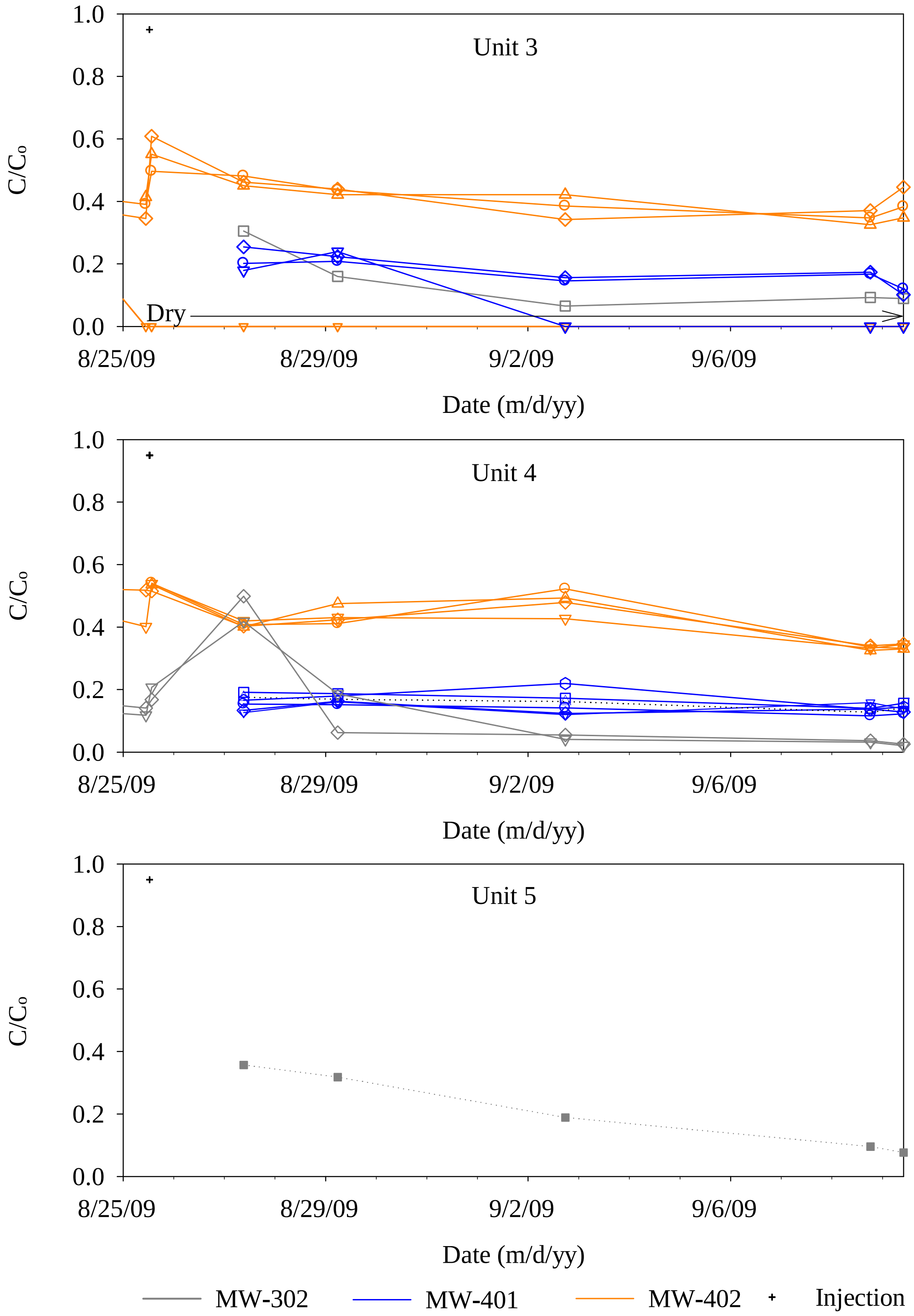


Figure E.22: Tracer breakthrough curves at Row 1 following Injection 7 at multilevel wells MW-302, MW-401 and MW-402. Multilevel well sampling points dry in MW-402 (1) at time of injection. MW-401 (1) dry from September 9, 2009 and onwards.

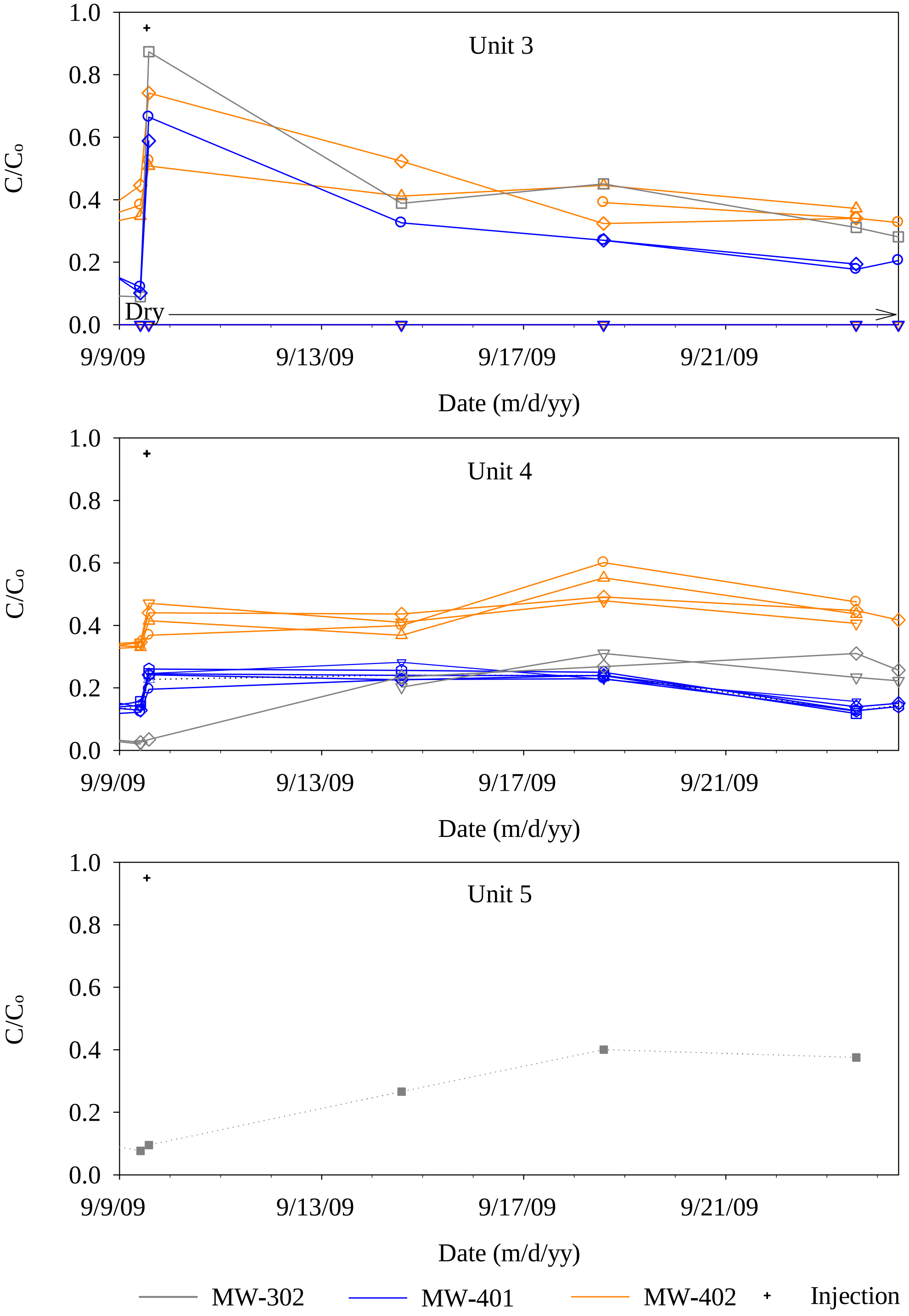


Figure E.23: Tracer breakthrough curves at Row 1 following Injection 8 at multilevel wells MW-302, MW-401 and MW-402. Multilevel well sampling points dry in MW-401 (1) and MW-402 (1) at time of injection.

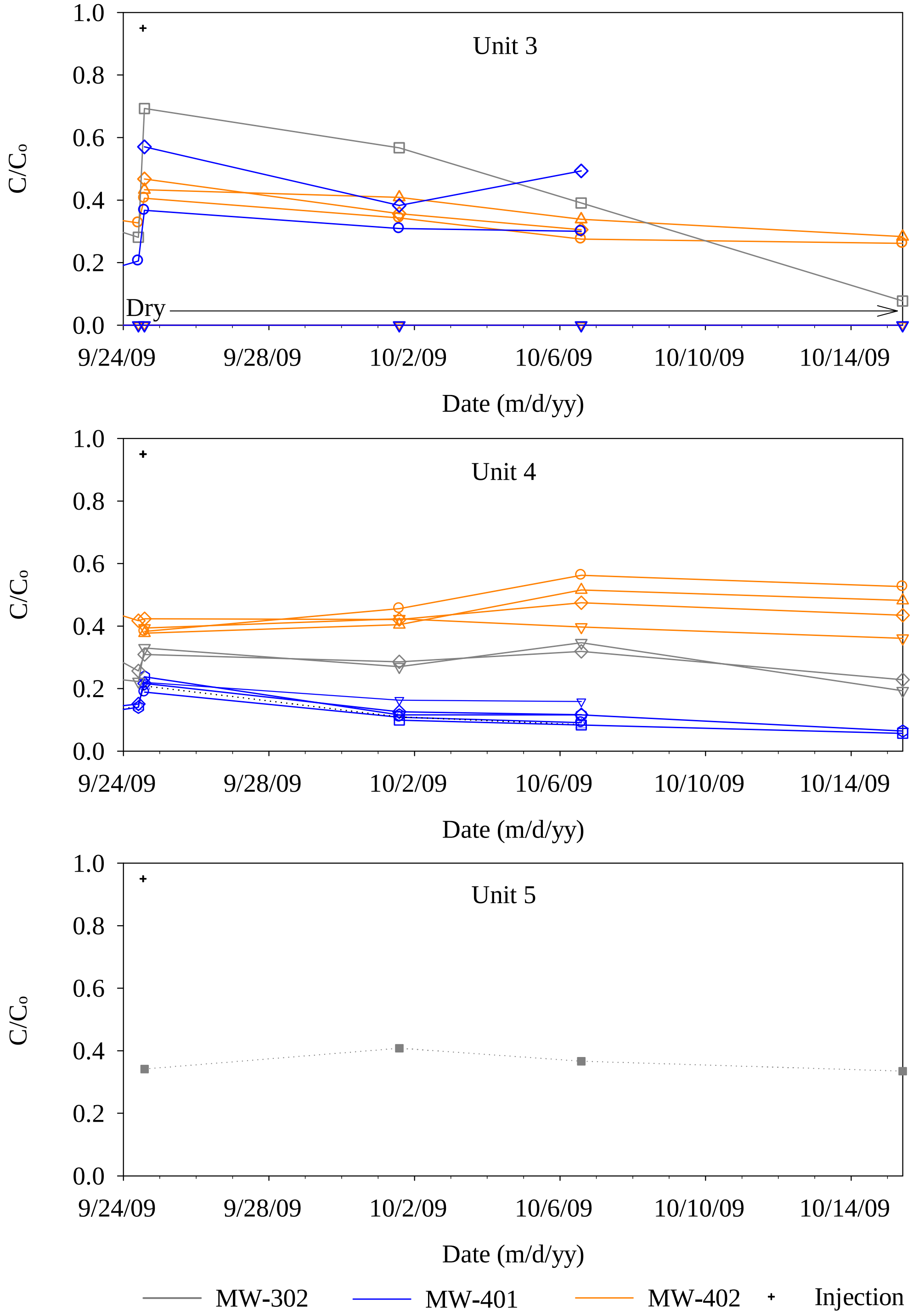


Figure E.24: Tracer breakthrough curves at Row 1 following Injection 9 at multilevel wells MW-302, MW-401 and MW-402. Multilevel well sampling points dry in MW-401 (1) and MW-402 (1) at time of injection.

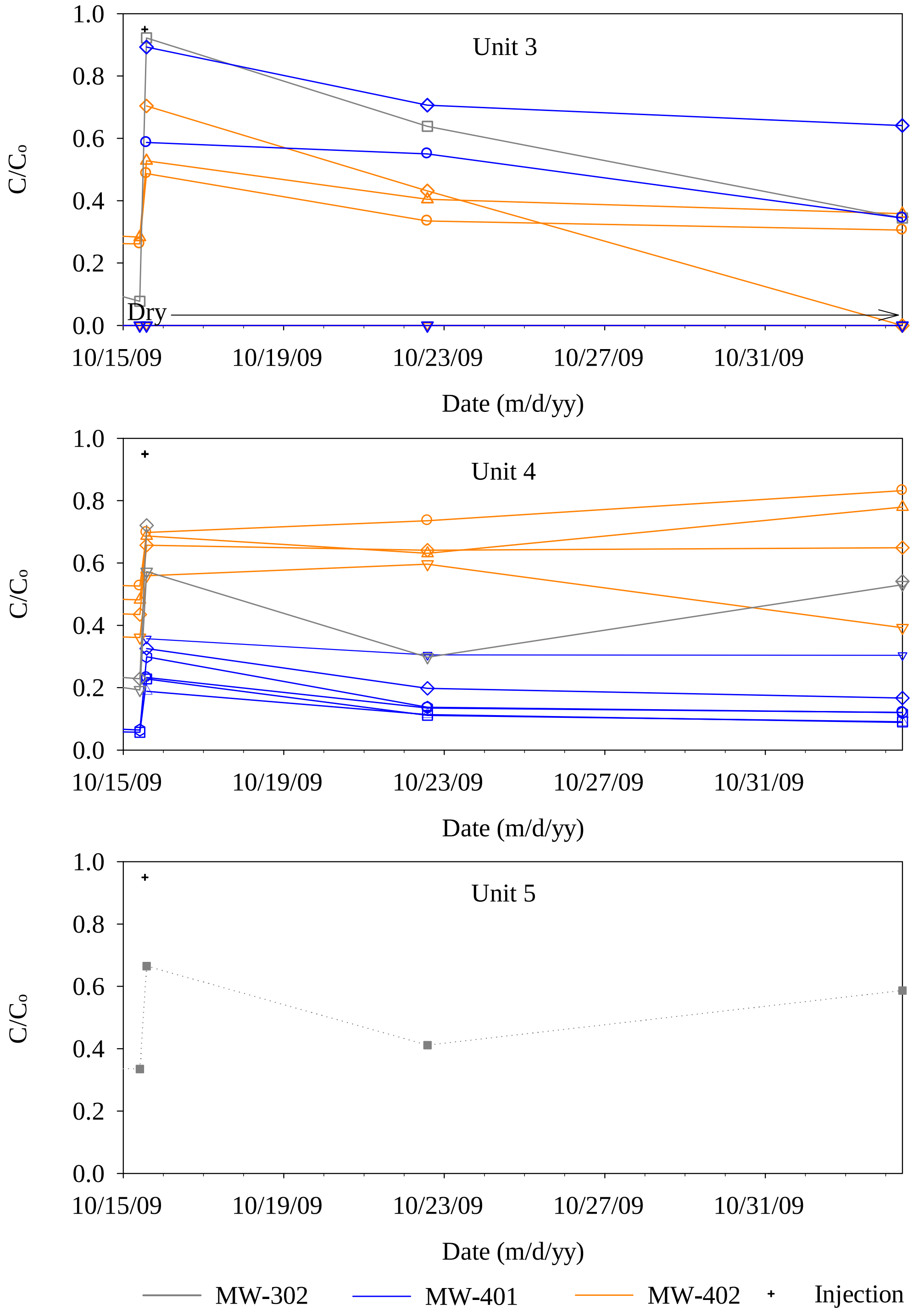


Figure E.25: Tracer breakthrough curves at Row 1 following Injection 10 at multilevel wells MW-302, MW-401 and MW-402. Multilevel well sampling points dry in MW-401 (1) and MW-402 (1) at time of injection.

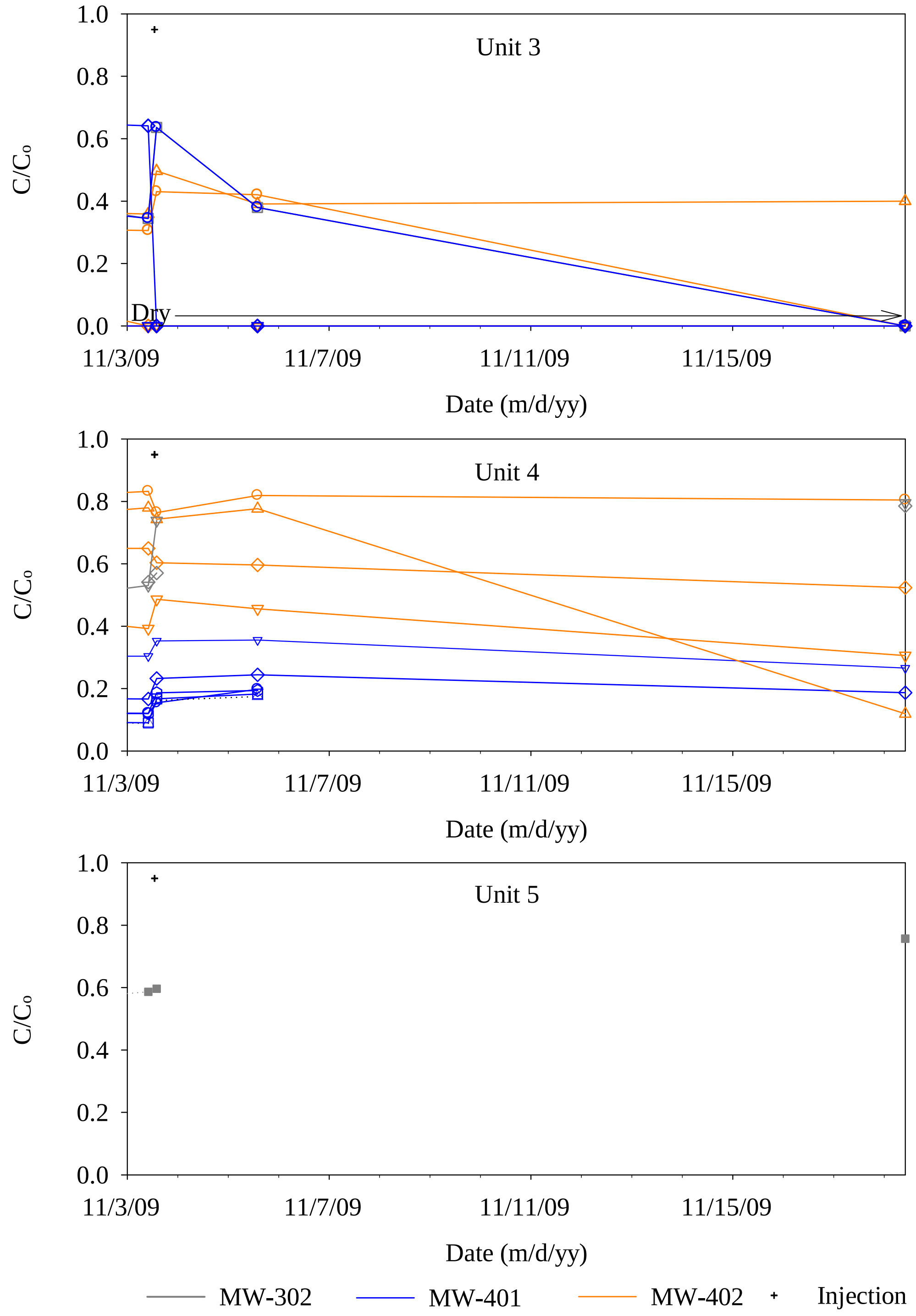


Figure E.26: Tracer breakthrough curves at Row 1 following Injection 11 at multilevel wells MW-302, MW-401 and MW-402. Multilevel well sampling points dry in MW-302 (6), MW-401 (1 & 2) and MW-402 (1 & 2) at time of injection.

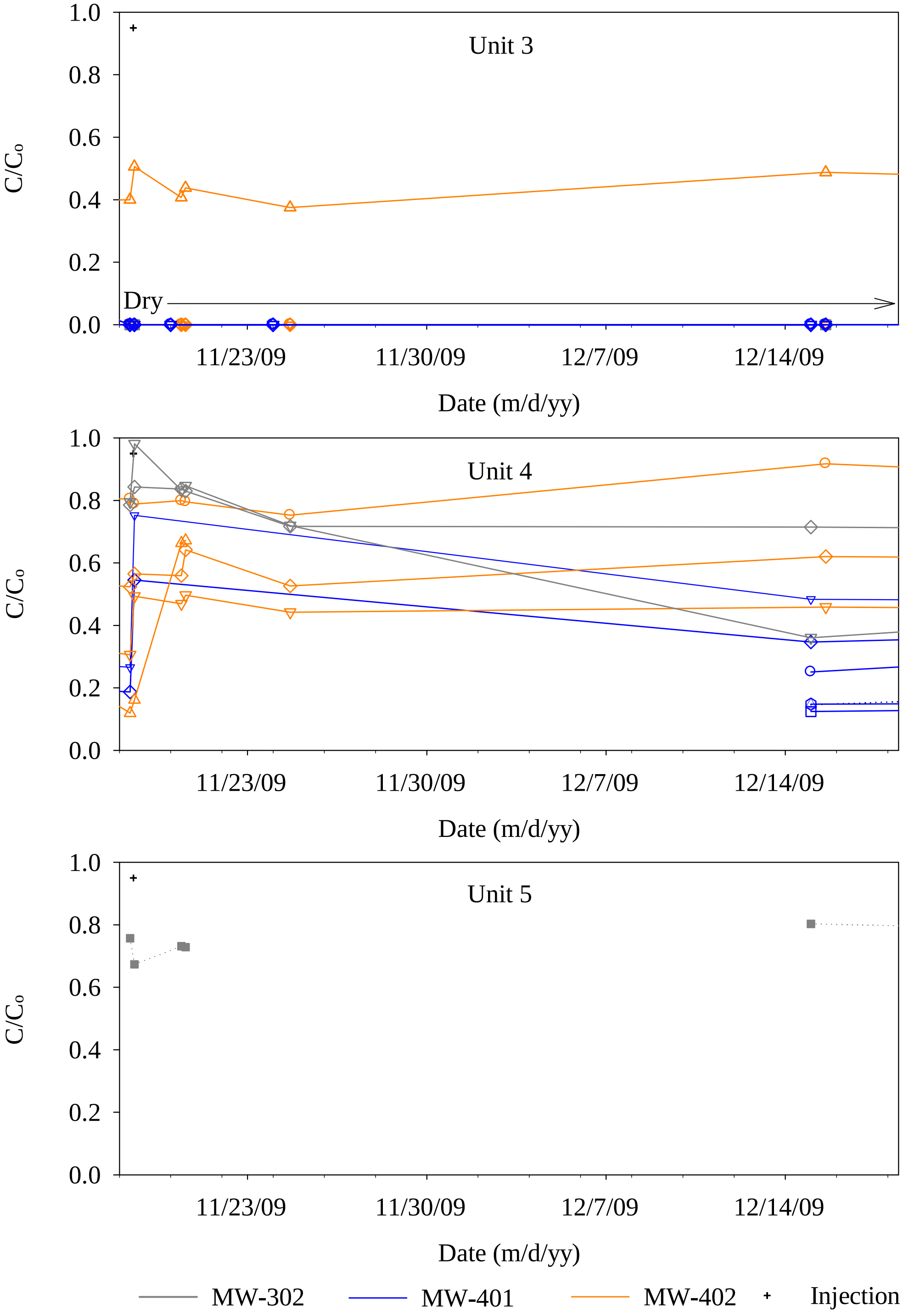


Figure E.27: Tracer breakthrough curves at Row 1 following Injection 12 at multilevel wells MW-302, MW-401 and MW-402. Multilevel well sampling points dry in MW-302 (6), MW-401 (1, 2 & 3) and MW-402 (1, 2, 3) at time of injection.

Table E.8 Method A: Average Linear Groundwater (Remedial Pulse Velocity) at the Injection Well MW-501

Injection No.	Date	Volume Injected (m^3)	ROI (m)	i	$t_{0.5}$ (days)	v_{MW-501} (m/day)	k
1	28-Jul-09	2.06	1.42	0.007	3.5	0.40	2.1E-04
2	5-Aug-09	2.07	1.42	0.007	2.0	0.71	3.8E-04
3	7-Aug-09	2.09	1.43	0.007	3.3	0.43	2.3E-04
4	10-Aug-09	2.13	1.44	0.007	3.2	0.45	2.4E-04
5	13-Aug-09	2.09	1.43	0.006	3.5	0.41	2.5E-04
6	17-Aug-09	2.13	1.44	0.006	3.8	0.38	2.3E-04
7	25-Aug-09	2.10	1.43	0.006	1.5	0.96	5.9E-04
8	9-Sep-09	2.11	1.43	0.004	2.0	0.72	6.6E-04
9	24-Sep-09	2.05	1.41	0.005	12.7	0.11	8.2E-05
10	15-Oct-09	2.08	1.42	0.003	-	-	
11	3-Nov-09	1.95	1.38	0.002	-	-	
12	18-Nov-09	2.02	1.40	0.003	-	<0.01	

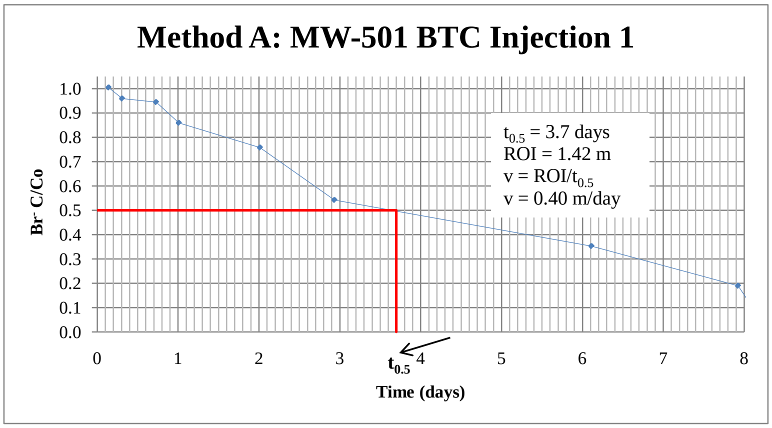

Method A: MW-501 BTC Injection 1

Table E.9 Method A: Average Linear Groundwater (Remedial Pulse Velocity) in Sand Unit 2 (MW-302-5)

Injection No.	Date	Volume Injected (m^3)	ROI (m)	i	$t_{0.5}$ (days)	$v_{Unit\ 2}$ (m/day)
1	28-Jul-09	2.06	1.42	0.007	0.7	1.91
2	5-Aug-09	2.07	1.42	0.007	0.3	**4.73**
3	7-Aug-09	2.09	1.43	0.007	1.7	0.85
4	10-Aug-09	2.13	1.44	0.007	2.9	0.49
5	13-Aug-09	2.09	1.43	0.006	3.6	0.40
6	17-Aug-09	2.13	1.44	0.006	dry	-
7	25-Aug-09	2.10	1.43	0.006	dry	-
8	9-Sep-09	2.11	1.43	0.004	dry	-
9	24-Sep-09	2.05	1.41	0.005	dry	-
10	15-Oct-09	2.08	1.42	0.003	dry	-
11	3-Nov-09	1.95	1.38	0.002	dry	-
12	18-Nov-09	2.02	1.40	0.003	dry	-

Average v (m/day)	0.91
STDEV	0.69

BOLD outlier

Table E.10 Method A: Average Linear Groundwater (Remedial Pulse Velocity) in Sand and Gravel Unit 3 (MW-302-6, MW-402-1, MW-402-2, MW-402-3 and MW-402-4)

Injection No.	Date	Volume Injected (m^3)	ROI (m)	i	MW-302-6 $t_{0.5}$ (days)	MW-302-6 v (m/day)	MW-402-1 $t_{0.5}$ (days)	MW-402-1 v (m/day)	MW-402-2 $t_{0.5}$ (days)	MW-402-2 v (m/day)	MW-402-3 $t_{0.5}$ (days)	MW-402-3 v (m/day)	MW-402-4 $t_{0.5}$ (days)	MW-402-4 v (m/day)	Unit 3 Average v (m/day)	Unit 3 STDEV v (m/day)	k (m/s)
1	28-Jul-09	2.06	1.42	0.007	0.7	1.91	1.2	1.20	1.2	1.18	3.0	0.47	6.1	0.24	1.00	0.67	5.3E-04
2	5-Aug-09	2.07	1.42	0.007	1.0	1.48	4.9	0.29	3.2	0.44	5.1	0.28	-	-	0.62	0.58	3.3E-04
3	7-Aug-09	2.09	1.43	0.007	0.9	1.58	5.5	0.26	6.0	0.24	-	-	-	-	0.69	0.77	3.7E-04
4	10-Aug-09	2.13	1.44	0.007	1.5	0.95	11.0	0.13	4.3	0.33	8.2	0.17	9.0	0.16	0.35	0.34	1.8E-04
5	13-Aug-09	2.09	1.43	0.006	-	-	-	-	4.1	0.34	-	-	-	-	0.34	-	2.1E-04
6	17-Aug-09	2.13	1.44	0.006	0.5	2.76	3.7	0.38	8.8	0.16	13.6	0.10	5.6	0.26	0.73	1.14	4.5E-04
7	25-Aug-09	2.10	1.43	0.006	-	-	-	-	13.9	0.10	30.0	0.05	25.3	0.06	0.07	0.03	4.3E-05
8	9-Sep-09	2.11	1.43	0.004	9.0	0.16	-	-	8.5	0.17	20.9	0.07	32.2	0.04	0.11	0.06	1.0E-04
9	24-Sep-09	2.05	1.41	0.005	13.0	0.11	-	-	22.3	0.06	41.8	0.03	34.5	0.04	0.06	0.03	4.6E-05
10	15-Oct-09	2.08	1.42	0.003	dry	-	dry	-	6.1	0.2	18.3	0.1	16.9	0.1	0.13	0.09	1.6E-04
11	3-Nov-09	1.95	1.38	0.002	dry	-	dry	-	dry	-	dry	-	-	-	-	-	-
12	18-Nov-09	2.02	1.40	0.003	dry	-	dry	-	dry	-	dry	-	-	-	-	-	-

	MW-302-6 v (m/day)	MW-402-1 v (m/day)	MW-402-2 v (m/day)	MW-402-3 v (m/day)	MW-402-4 v (m/day)
Average v (m/day)	1.28	0.45	0.33	0.16	0.13
STDEV	0.96	0.43	0.32	0.15	0.09

-	no representative data

Table E.11 Method A: Average Linear Groundwater (Remedial Pulse Velocity) in Sand Unit 4 (MW-302-7, MW-302-8, MW-402-5 and MW-402-6)

Injection No.	Date	Volume Injected (m^3)	ROI (m)	i	MW-302-7 $t_{0.5}$ (days)	MW-302-7 v (m/day)	MW-302-8 $t_{0.5}$ (days)	MW-302-8 v (m/day)	MW-402-5 $t_{0.5}$ (days)	MW-402-5 v (m/day)	MW-402-6 $t_{0.5}$ (days)	MW-402-6 v (m/day)	Unit 4 Average v (m/day)	Unit 4 STDEV v (m/day)
1	28-Jul-09	2.06	1.42	0.007	1.5	0.93	1.8	0.78	6.1	0.23	1.4	0.98	0.73	0.34
2	5-Aug-09	2.07	1.42	0.007	2.1	0.68	1.7	0.83	-	-	-	-	0.76	0.11
3	7-Aug-09	2.09	1.43	0.007	2.8	0.51	2.3	0.61	-	-	-	-	0.56	0.08
4	10-Aug-09	2.13	1.44	0.007	2.7	0.54	2.6	0.56	11.1	0.13	-	-	0.41	0.24
5	13-Aug-09	2.09	1.43	0.006	3.7	0.39	-	-	-	-	-	-	0.39	
6	17-Aug-09	2.13	1.44	0.006	7.1	0.20	3.8	0.38	13.6	0.11	1.8	0.82	0.38	0.31
7	25-Aug-09	2.10	1.43	0.006	-	-	1.8	0.78	33.8	0.04	32.9	0.04	0.29	0.42
8	9-Sep-09	2.11	1.43	0.004	-	-	-	-	-	-	-	-	-	
9	24-Sep-09	2.05	1.41	0.005	-	-	-	-	26.3	0.05	-	-	0.05	
10	15-Oct-09	2.08	1.42	0.003	-	-	45.2	0.03	25.9	0.05	-	-	0.04	0.02
11	3-Nov-09	1.95	1.38	0.002	-	-	-	-	19.5	0.1	71.0	0.02	0.05	0.0
12	18-Nov-09	2.02	1.40	0.003	-	-	588.6	0.002	-	-	-	-	0.002	-
				Average v (m/day)		0.54		0.50		0.10		0.47		
				STDEV		0.25		0.33		0.07		0.51		

- no representative data

Appendix F

Analysis of Nitrate Utilization

Nitrate Utilization Calculations MW-402

	Time	ln (Cr/Ctr)
Injection 6	0.0417	-0.8795
402-2	0.2188	-1.0645
	0.559	-1.1611
	0.9375	-1.6803
	1.1389	-1.8058
	2.1667	-2.7367
	3	-3.6396
	4.0035	-3.6026
	6.3576	-4.2544
	8.0174	-3.1092

where r - reactant (NO3-) and tr is the tracer (Br-)

Well ID	Injection #	Time (days)	Br- mg/L	C/Co Br-	NO3- mg/L	C/Co NO3-	NO2- mg/L
402-2	6	0.0417	109	0.5767	30.3	0.2393	7.1
Sand & Gravel	44 mg/L NO3-	0.2188	85.7	0.4534	19.8	0.1564	6.7
		0.559	123	0.6508	25.8	0.2038	8.3
		0.9375	129	0.6825	16.1	0.1272	8
		1.1389	119	0.6296	13.1	0.1035	7.5
		2.1667	106	0.5608	4.6	0.0363	7.6
		3	108	0.5714	1.9	0.015	7.7
		4.0035	98.6	0.5217	1.8	0.0142	8
		6.3576	84.1	0.445	0.8	6.32E-03	8.9
		8.0174	60.2	0.3185	1.8	0.0142	7.3
	7	0.0417	83.2	0.4674	27.3	0.1386	8
	200 mg/L NO3-	1.8576	54	0.3034	11.3	0.0574	5.8
		4.2153	57.1	0.3208	4.1	0.0208	7.6
		12.2118	64.7	0.3635	1.9	9.64E-03	8.4
		18.2396	53.7	0.3017	1.3	6.60E-03	8.4

	Time	ln (Cr/Ctr)					
	0	0					
Injection 6	0.04	-0.88	slope	-0.3656	-1.4266		
402-2	0.22	-1.06	(+/-)	0.0924	0.3418		
	0.56	-1.16	R	0.662	0.7563		
	0.94	-1.68		15.6712	8		
	1.14	-1.81		8.9634	4.5757		
	2.17	-2.74					
	3.00	-3.64					
	4.00	-3.60					
	6.36	-4.25					
	8.02	-3.11					
	0.00	0.00					
Injection 7	0.04	-1.22	slope	-0.1407	-1.585		
402-2	1.86	-1.67	(+/-)	0.0314	0.3153		
	4.22	-2.74	R	0.8697	0.4824		
	12.21	-3.63		20.0303	3		
	18.24	-3.82		4.6622	0.6983		
	0.00	0.00				Select 402-4-12	
Injection 12	0.05	-0.61	slope	-0.7218	-0.5254	0.0486	-0.6091
402-4	1.92	-3.83	(+/-)	0	0	5.0833	-3.5843
	4.00	-4.00	R	1	0		
	5.08	-3.58		#NUM!	0		
	26.08	-3.15		0.909	0		

Injection 6	0.04	-0.88	slope	-0.7702	-0.9097	Injection 12	0.05	-0.61	0.0486
402-2	0.22	-1.06	(+/-)	0.0682	0.1369	402-4	1.92	-3.83	5.0833
	0.56	-1.16	R	0.9551	0.2557		4.00	-4.00	
	0.94	-1.68		127.5779	6		5.08	-3.58	
	1.14	-1.81		8.3407	0.3923		26.08	-3.15	
	2.17	-2.74							
	3.00	-3.64							
	4.00	-3.60							

SO42- mg/l	C/Co Br-	NO3- mg/L
40.2	0.5767	30.3
31	0.4534	19.8
46	0.6508	25.8
46.1	0.6825	16.1
45.3	0.6296	13.1
42.9	0.5608	4.6
39.6	0.5714	1.9
33.1	0.5217	1.8
23.4	0.445	0.8
14.5	0.3185	1.8
29.5	0.4674	27.3
19.1	0.3034	11.3
20	0.3208	4.1
20	0.3635	1.9
17.7	0.3017	1.3

Select 402-4-12	
0.0486	-0.6091
5.0833	-3.5843

-0.6091	0.0486	-0.6091
-3.5843	26.0833	-3.1483

Nitrate Utilization Calculations MW-302

	Date & Time	Time (days)	Br/Br	NO3/NO3	no3/br	ln (Cr/Ctr)	Time (days	ln (Cr/Ctr)
302-6	8/17/2009 15:10	0.0	0.9	0.6	0.6	-0.5	0.0	-0.5
	8/17/2009 19:25	0.2	0.7	0.4	0.5	-0.7	0.2	-0.7
	8/17/2009 23:35	0.6	0.6	0.2	0.5	-0.8	0.6	-0.8
	8/18/2009 8:40	0.9	0.4	0.2	0.3	-1.1	0.9	-1.1
	8/18/2009 13:30	1.1	0.3	0.2	0.5	-0.8	1.1	-0.8
	8/20/2009 10:25	3.0	0.2	0.0	0.1	-2.8	3.0	-2.8
	8/21/2009 10:30	4.0	0.1	0.0	0.1	-2.9	4.0	-2.9
302-7	11/18/2009 12:00	0.0	0.6	0.5	0.8	-0.2	0.0	-0.2
	11/18/2009 12:00	0.1	0.6	0.5	0.8	-0.2	0.1	-0.2
	11/20/2009 10:00	1.9	0.6	0.2	0.4	-0.9	1.9	-0.9
	11/22/2009 14:00	4.0	0.6	0.3	0.5	-0.8	4.0	-0.8
	11/24/2009 16:00	5.1	0.7	0.1	0.2	-1.6	5.1	-1.6
	11/24/2009 16:00	5.1	0.6	0.1	0.2	-1.6	5.1	-1.6
	12/15/2009 14:00	26.1	0.4	0.0	0.0	-4.4	26.1	-4.4

	Time (days)	Br/Br		no3/br	ln (Cr/Ctr)		ln (Cr/Ctr)	
	0	0					0	
302-6 Inj 6	0.04	-0.45	slope	-0.7	-0.4	per day	-0.45	per day
	0.22	-0.70	(+/-)	0.1	0.1		-0.70	
	0.56	-0.80	R	0.9	0.3		-0.80	
	0.94	-1.05		80.1	5.0		-1.05	
	1.15	-0.76		6.0	0.4		-0.76	
	3.00	-2.78					-2.78	
	4.00	-2.88					-2.88	
	0.00	0.00					0.00	
302-7 inj 7	1.86	-1.80	slope	-1.0	0.1		-1.80	
	4.22	-4.25	(+/-)	0.0	0.0		-4.25	
			R	1.0	0.0			
				3.0	0.0			
	Time (days)							
	0.00	0					0	
302-7-12	0.01	-0.25	slope	-0.15	-0.45		-0.25	
	0.07	-0.23	(+/-)	0.01	0.15		-0.23	
	1.92	-0.88	R	0.98	0.29		-0.88	
	5.08	-1.59		143.06	3.00		-1.59	
	26.08	-4.40		11.70	0.25		-4.40	
		Time						
302-7-7	8/27/2009 9:10	1.86	-1.80					
	8/29/2009 5:45	4.22	-4.25					

Nitrate Utilization Calculations MW-501

	Time	ln (Cr/Ctr)			
	0	0			
501-12	0.04	-0.19	slope	-0.10	-0.22
	5.08	-0.74	(+/-)	0.00	0.04
	26.08	-2.69	R	1.00	0.05

Theoretical estimation of the amount of nitrate consumed.

	Hypothetical NO3-		NO3 consumed	NO3 consumed		IC	IC
		Date & time	mg/L	mmol/L	Time (days)	Br/Br	NO3/NO3
402-4-12	5	11/18/2009 11:00	0	0	0.0139	0.2391	3.88E-03
	181	11/18/2009 14:00	69.0348	1.1135	0.0486	0.7288	0.3963
	101	11/20/2009 10:00	98.1396	1.5829	1.9167	0.4042	8.82E-03
	129	11/22/2009 14:00	126.1599	2.0348	4	0.5176	9.52E-03
	111	11/24/2009 16:00	107.1907	1.7289	5.0833	0.4446	0.0123
	127	12/15/2009 14:00	120.5982	1.9451	26.0833	0.5093	0.0219
		NO3 consumed	mmol/L				
302-7-12	183	40.44	0.6523	11/18/2009 12:00	6.94E-03		
	163	34	0.5484	11/18/2009 12:00	0.0701		
	165	96.6	1.5581	11/20/2009 10:00	1.9167		
	162	87.4	1.4097	11/22/2009 14:00	4		
	186	147.73	2.3827	11/24/2009 16:00	5.0833		
	166	132.58	2.1384	11/24/2009 16:00	5.0833		
	122	120.1	1.9371	12/15/2009 14:00	26.0833		
501-12							
			0	0	0		
			12.5464	0.2024	0.0417		
			64.5665	1.0414	5.0833		
			96.6062	1.5582	26.0833		

Results of Anion Analysis

Well ID	Injection	Time (days)	Br- mg/L	C/Co Br-	NO3- mg/L	C/Co NO3-	NO2- mg/L	SO42- mg/L	SO4/SO4	nitrite C/Co
402-2	6	0.04	109.00	0.58	30.30	0.24	7.10	40.20	0.75	1.29
		0.56	123.00	0.65	25.80	0.20	8.30	46.00	0.86	1.51
		0.94	129.00	0.68	16.10	0.13	8.00	46.10	0.86	1.45
		1.14	119.00	0.63	13.10	0.10	7.50	45.30	0.85	1.36
		2.17	106.00	0.56	4.60	0.04	7.60	42.90	0.80	1.38
		3.00	108.00	0.57	1.90	0.02	7.70	39.60	0.74	1.40
		4.00	98.60	0.52	1.80	0.01	8.00	33.10	0.62	1.45
		6.36	84.10	0.45	0.80	0.01	8.90	23.40	0.44	1.62
		8.02	60.20	0.32	1.80	0.01	7.30	14.50	0.27	1.33
	7	0.04	83.20	0.47	27.30	0.14	8.00	29.50	0.47	1.45
	200 mg/L NO3-	1.86	54.00	0.30	11.30	0.06	5.80	19.10	0.31	1.05
		4.22	57.10	0.32	4.10	0.02	7.60	20.00	0.32	1.38
		12.21	64.70	0.36	1.90	0.01	8.40	20.00	0.32	1.53
		18.24	53.70	0.30	1.30	0.01	8.40	17.70	0.28	1.53

		Sample Name	Cl- (mg/L)	NO2- (mg/L)		SO4= (mg/l)	so4/so4	Br- (mg/l)		NO3- (mg/L)	
402-4-12	TIme (days)	Rt=	3.97	4.587	NO2/NO2	5.237		5.66	Br/Br	6.393	
	0.01	402-4-1	350.4	13.2		3.8		46.2	0.2391	1.1	3.88E-03
	0.05	402-4-5	115.2	11.7	1.4444	55.7	1.0529	140.8	0.7288	112.4	0.3963
	26.08	402-4-68	216.4	14.7	1.8148	4.7	0.0846	98.4	0.5093	6.2	0.0219

Well ID	Injection	Time (days)	Br- mg/L	C/Co Br-	NO3- mg/L	C/Co NO3-	NO2- mg/L	SO42- mg/L	SO4/SO4
302-6-6	6	0.04	169.00	0.89	72.10	0.57	5.50	51.80	0.97
Sand & Gravel	90 mg/L NO3-	0.22	136.00	0.72	45.10	0.36	8.00	46.00	0.86
		0.56	104.00	0.55	31.40	0.25	8.00	39.00	0.73
		0.94	84.00	0.44	19.60	0.15	9.20	35.90	0.67
		1.15	63.10	0.33	19.80	0.16	8.00	23.70	0.44
		3.00	33.70	0.18	1.40	0.01	8.00	13.10	0.25
		4.00	26.50	0.14	1.00	0.01	6.70	9.60	0.18

Sample Name	Cl- (mg/L)	NO2- (mg/L)	NO2-	SO4= (mg/l)		Br- (mg/l)	Br/Br	NO3- (mg/L)	NO3/NO3	TIme
Rt=	3.97	4.587		5.237		5.66		6.393		
302-7-8	35.5	11.75		65.41	1.24	183.47	0.65	143.03	0.50	0.01
302-7-8	34	8.5		62.50	1.18	163.20	0.58	129.20	0.46	0.07
302-7-11	37.2	13.25		72.40	1.37	165.20	0.58	68.60	0.24	1.92
302-7-67	43.97	14.69		73.44	1.39	166.40	0.59	33.82	0.12	5.08
302-7-68	170	9		54.10	1.02	121.60	0.43	1.50	0.01	26.08
		Br/Br	NO3/NO3	Nitrite	sulphate C/Co					
501-12	0.0417	0.8778	0.7264	9.1	1.0499					
	5.0833	0.9193	0.4401	27.19	1.349					
	26.0833	0.9151	0.0621	29.2	1.3611					
	126	0.53	0.05	0						

Time	Br/Br	NO3/NO3	SO42-	NO2-
0.01	0.24	0.00	0.07	13.20
0.05	0.73	0.40	1.05	11.70
1.92	0.40	0.01	0.29	12.30
4.00	0.52	0.01	0.36	13.40
5.08	0.44	0.01	0.31	12.40
26.08	0.51	0.02	0.09	14.70